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Technologies and Costs for the Removal of Fluoride from Potable Water Supplies (Draft)

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Prepared for

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TECHNOLOGIES AND COSTS FOR THE REMOVAL OF FLUORIDE FROM POTABLE WATER SUPPLIES

for
Science and Technology Branch
Criteria and Standards Division
Office of Drinking Water
U.S. Environmental Protection Agency
Washington, D.C.

May 25, 1984

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16. ABSTRACT

The Office of Drinking Water (ODW), U. S. Environmental Protection Agency (USEPA) has prepaired a draft document entitled Technologies and Costs for the Removal of Fluoride in Potable Water Supplies. This Document is a preliminary draft which has not, as yet, been formally released by ODW, USEPA and should not be construed at this stage to represent Agency policy. This Document is a review of the technical information on the methods currently available for the removal of fluoride from drinking water. The document presents information on both the cost and effectiveness of available methods.

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NOTICE

This document has not been formally released by the U.S. Environmental Protection Agency (EPA) and should not at this stage be construed to represent Agency policy. It is being circulated for comment on its technical accuracy and policy implications.

INTRODUCTION

This document identifies technologies that might be used by community water systems in achieving compliance with the National Primary Drinking Water Regulations. The technologies available to a community searching for the most economical and effective means to comply with the fluoride Maximum Contaminant Level (MCL) include modification of existing treatment systems, installation of new systems and may include the selection of other water sources, such as bottled water or alternate raw water sources.

It is not the intention of EPA to require any system to use a particular technology to achieve compliance with the fluoride MCL. Instead, the responsibility is retained by the individual water systems to select one or more procedures that are optimal for their particular water supply situation. Whichever individual or combination of technologies is ultimately selected by a water supplier to achieve compliance with the MCL must be based upon a case by case technical evaluation of the system's entire treatment process, and an assessment of the economics involved. However, the major factors that must be considered include:

- quality and type of water source
- degree of fluoride contamination
- economies of scale and the cost of water
- treatment requirements and efficient waste disposal.

The information provided herein is intended to aid a system in selecting the best technology for achieving the fluoride MCL.

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It provides the user with an evaluation of the various methods in use today for providing acceptable drinking water supplies.

Some methods are more complex or more expensive than others. The selection of a technology by a community may include engineering studies and/or pilot-plant operations to determine the probability that any of the methods will reduce the level of fluoride for that system. Technologies currently in a development stage for the removal of fluorides are identified because of their adaptability to treatment of drinking water supplies. It is expected that after development and pilot-scale testing, these methods may be technically and economically feasible for specific situations.

BACKGROUND

Fluoride commonly occurs in the earth's crust as fluorspar (CaF_2), cryolite (Na_3AlF_6), and fluorapatite [$Ca_{10}F_2(PO_4)_6$] and ranks thirteenth among the elements in order of abundance. Fluoride is present in seawater at a concentration of approximately 1.4 milligrams per liter (mg/L), and concentrations as high as 9 to 10 mg/L are not uncommon in some groundwaters.

In addition to its natural occurrence, fluoride is relocated and concentrated in the environment as a result of industrial activities. It is widely used in many manufacturing processes and is present in large quantities in effluents from glass manufacture, electroplating operations, aluminum and steel production, and the manufacture of electronic parts. Furthermore, large quantities of fluorides are released when fertilizer is manufactured from phosphate rock containing fluorapatite.

The chemical quality of a water supply is changed by the solution of minerals from geologic formations, and the fluoride content of groundwater sources may be increased when in contact with fluoride-bearing minerals. Additionally, climatic conditions and biochemical factors affect the types and quantity of dissolved solids present in a water supply. For example, during the weathering process, fluoride and other chemicals in rocks dissolve and pass into the water.

Unless contaminated by fluoride-laden wastewaters, the concentration in surface water is normally low. In many systems, controlled fluoridation is used to provide optimum fluoride concentrations in finished drinking water supplies to reduce the incidence of dental caries. However, when the concentration exceeds the MCL, treatment to remove fluoride should be applied. The technologies and their removal efficiencies applicable to reducing fluorides from drinking water sources are summarized in Table A-1, Appendix A. Since an optimum fluoride concentration is desired in drinking water supplies, the blending of treated

water with untreated water is feasible. Therefore, some technologies that remove a high percentage of the fluorides may require blending to maintain an optimum fluoride concentration in the finished water. Variations in the physical and chemical characteristics of source water, initial fluoride concentration, and other site specific conditions will affect removal efficiencies of the methods identified. These factors are a basis for the range in removal efficiencies shown in the bar chart, Figure A-1, Appendix A.

Analytical methods for the quantitative determination of fluorides in drinking water are presented in Appendix B. These methods, listed in 40 CFR Part 141.23, dated August 27, 1980,[1] are the approved current analytical techniques for compliance with the fluoride MCL requirements. The optimum fluoride concentration range and detection limits for some of the analytical techniques vary with presence of other substances in the water being sampled.

TECHNOLOGIES FOR REDUCING FLUORIDE

These technologies are water treatment processes or technologies within the technical and financial capability of most public water systems. Some technologies identified may be more complex and expensive than others but because of site specific conditions and system size, are more applicable and effective for complying with the fluoride MCL. Prior to implementing a technology, engineering studies of the methods identified to reduce fluoride should be made specific to the site requirements. The engineering study should select a technically feasible and cost effective method for a specific location. In some cases a simple survey may suffice, whereas in others, extensive chemical analysis, design and performance data will be required. The study may include laboratory tests and/or pilot-plant operations to cover seasonal variations, preliminary designs and estimated capital and operating costs for full scale treatment. The evaluation of other options, such as bottled water, point-of-use, regionalization and alternate water sources, may be included. Cost estimates for such engineering studies will vary, and as the systems increase in size, the engineering requirements increase and cost of the study increases accordingly. For this analysis the range in cost estimates for the engineering study are from $25,000 for the smallest system involving only survey data to $250,000 for the largest system requiring laboratory analysis and pilot-plant operations.

The following methods identified represent the most cost effective methods for providing drinking water complying with the fluoride MCL requirements.

1. ACTIVATED ALUMINA.
2. REVERSE OSMOSIS.
3. LIME SOFTENING, MODIFIED.
4. BOTTLED WATER.

5. POINT-OF-USE
   A. ACTIVATED ALUMINA
   B. REVERSE OSMOSIS.
6. REGIONALIZATION.
7. ALTERNATE SOURCE.

Discussion of Technologies

1. Activated Alumina: Activated alumina can be used as an exchange media for defluoridation for a majority of water supplies with excessive fluoride and/or arsenic. The sorption of fluoride on activated alumina is rapid. Test results indicate that the majority of fluoride is removed during the first 10 minutes of exposure to activated alumina, with smaller removal occurring up to 30 minutes after the initial exposure.(2)

Activated alumina is manufactured for use as an analytical reagent and as a dessicant. The material is a by-product of aluminum production. It is primarily an aluminum oxide which has been activated by exposure to high temperature. The material is extremely porous, ground into granular form and screened into various mesh sizes. The crystalline structure of activated alumina consists of local sites of negative charge within a cationic lattice. There are also positively-charged sites which can accommodate anion "adsorption." It is through this process (generally thought to be a combination of ion exchange and adsorption) that activated alumina acts to remove fluoride from water.

The capacity of activated alumina for fluoride is proportional to the concentration of fluoride in the raw water. The higher the level of fluoride, the greater the adsorption capacity. At a plant located in Bartlett, Texas, the fluoride capacity decreased from 700 grains/cubic foot (grains/cuft) to 450 grains/cuft fluoride when the influent fluoride concentration was reduced from 8 mg/L to 3 mg/L.(2) This relationship is

characteristic of sorption processes and is quantitatively described by adsorption isotherms. The significance of such adsorption isotherms is that exchange capacity of a given media varies with feed water fluoride level.[2]

Alkalinity of the water at high pH ranges, especially when hydroxides are present, has a marked effect on the adsorption capacity of activated alumina for fluoride removal. High fluoride capacities have been obtained in waters having low alkalinities.[2] As the alkalinity increases, the fluoride capacity generally decreases, because the ions responsible for alkalinity compete with fluoride ions for adsorption sites on the media. Fluoride capacities apparently are not reduced significantly by competition from chlorides or bicarbonates.

From bench scale tests, a raw water pH in the range of 5.0 to 6.0 can result in removal capacities in excess of 2,000 grains/cuft of media.[3] At pH 5.5 the fluoride adsorption capacity is maximum.[4] However, to depress the pH to 5.5 requires continuous feed of an acid and post-treatment to elevate effluent pH for distribution. The defluoridated water pH should be adjusted to a less corrosive level at the end of the treatment process. This can be achieved by aeration to release carbon dioxide, injection of sodium hydroxide, or by blending the processed water with raw water. Other water stabilization processes, such as lime or calcium carbonate addition, are also technically suitable. These create additional costs and a trade-off analysis should be made prior to the design of full scale plants.

Several plants have been constructed using activated alumina as the ion exchange media. The best known and longest operating was constructed in 1952 in Bartlett, Texas. At this plant, an open contact tank was filled with 28 to 48 mesh activated alumina. Raw water with a fluoride concentration of 8 mg/L and pH 7 was passed by gravity through a 500 cuft bed of activated alumina. The fluoride concentration was reduced from 8 mg/L to 1 mg/L at a plant flow of 400 gallons per minute (gpm). Reported

capacity was 400 to 700 grains/cuft.[5] After treating about 450,000 gallons of raw water with 8 mg/L of fluorides, and 1,000,000 gallons when the raw water source was changed to 3.0 mg/L, the media was regenerated. The regeneration equipment included a 6,000 gallon caustic solution tank and a system for measuring, diluting, and metering acid solutions. Regenerant wastes from the process were discharged to the sanitary sewer system. Dilution of the regeneration wastewater in the sewer and at the wastewater treatment plant was sufficient, thus producing no adverse effect on wastewater treatment. The total amount of raw water used per regeneration was about 68,500 gallons or 15 percent of treated water flow. This plant was taken out of service in 1977.[5]

Other plants currently in operation use the same type of equipment but use evaporation ponds to contain the regeneration wastewater. The Desert Center Plant in California, constructed in 1970 using the same type of equipment, has a rated capacity of 1.5 million gallons per day (mgd) and is lowering the fluoride concentration from 8 mg/L to less than 1 mg/L.[2,3,4,6,7] The Rencon Water Company plant near Vail, Arizona, also using similar equipment, has a rated capacity of 0.7 mgd and has been reducing the fluoride from 5 mg/L to below 1 mg/L.[2,3,4,7] The activated alumina plant at Gila Bend, Arizona, became operational in May of 1978. Two contact tanks are operated on staggered cycles of regeneration. The plant treats approximately 650,000 gallons per day (gpd) serving a population of 2,200 permanent residents as well as numerous motels and restaurants catering to transient persons. The fluoride level is reduced from 4.5 mg/L to 1.0 mg/L.[3,4,8]

Lined pressure contactors or open lined tanks are suitable vessels for activated alumina. Typically, two contact tanks, with bed depths of five or ten feet of activated alumina, would be installed at a water treatment plant requiring fluoride removal, and operated on staggered cycles. Depending upon the required fluoride removal, only a portion of the raw water may

require treatment. The treated water would then be blended with the bypass water as shown in Figure 1.

Following its useful life, the activated alumina can be regenerated. Regeneration equipment would include caustic soda storage and feed facilities, acid storage and feed facilities, and a regenerant waste handling facility. Additionally, pretreatment facilities should be evaluated to optimize fluoride removals and reduce the portion of the raw water requiring treatment ahead of blending. It should be noted that the aluminum concentrations of treated water from activated alumina systems may increase. In the initial phase of operation of activated alumina filters, several mg/L of aluminum have been measured.[9] However, the aluminum concentrations decreased with water use to trace levels. In some instances the aluminum measured in treated water is believed to be sloughing of the fines, especially after addition of makeup media to the filter, or following regeneration.

The degradation and loss of activated alumina occurs largely during the regeneration cycle. Although there may be considerable losses due to mechanical attrition during the backwash operations, the chemical degradation during regeneration is due largely to the effects of the NaOH solution. The acid neutralization apparently is less damaging than the NaOH treatment. Laboratory tests have shown that the amount of media lost during each regeneration cycle is a dual function of the concentration of the NaOH regenerant and the time of contact with the media.

In addition to the treatment system, regenerant waste handling and disposal facilities must be provided. Disposal options include discharge into the sanitary sewer, hauling to a landfill and use of evaporation lagoons. The discharge of this waste to the sanitary sewer would have to comply with any existing discharge ordinances. The use of evaporation lagoons would be especially appealing in hot, arid climates, such as the southwestern United States. Hauling the waste to a landfill

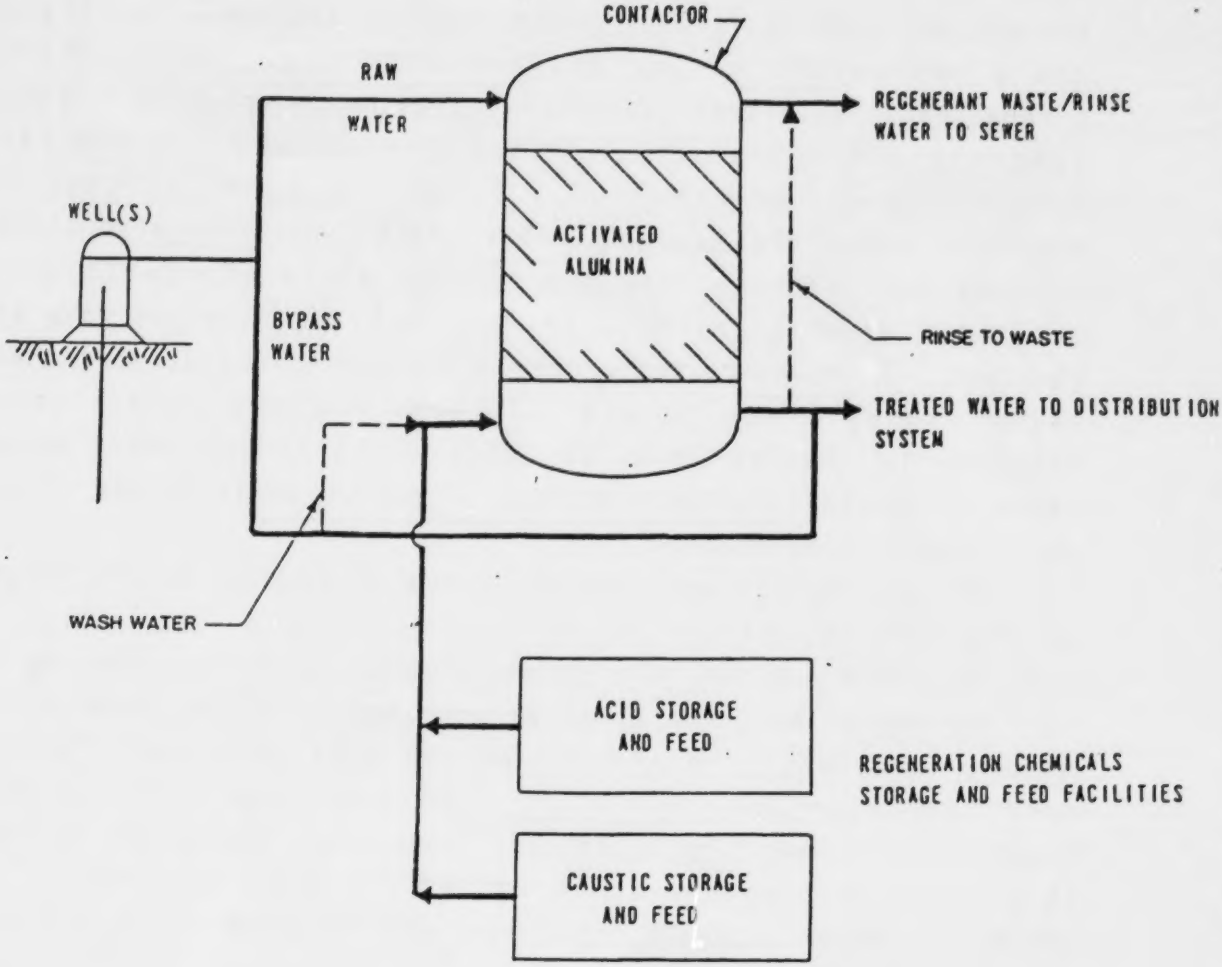


FIGURE 1 SCHEMATIC OF ACTIVATED ALUMINA PROCESS

would probably be the least desirable alternative due to the high cost associated with hauling a liquid waste.

2. Reverse Osmosis: Reverse osmosis (RO) is a treatment method capable of removing fluorides and total dissolved solids from drinking water supplies. Reverse osmosis is a comparatively new process having been used commercially less than 20 years. The first practical reverse osmosis membrane, cellulose acetate, was demonstrated in the laboratory in 1960. The process has developed rapidly, and there are now more than 300 reverse osmosis plants of greater than 25,000 gpd capacity treating brackish waters in the U.S.[4,10,11] In spite of the large number of reverse osmosis plants, only very limited experience is available on the removal of fluoride. This is due largely to the fact that existing plants were not installed to meet a specific fluoride problem. Also, the feed waters for these plants have tended to be low in fluoride. However, test data indicate that reverse osmosis does remove fluorides and will operate effectively as a fluoride removal treatment for small and large size systems.[12] A typical RO treatment system is shown on Figure 2.

Reverse osmosis pilot-plant operations have shown fluoride removal efficiencies greater than 90 percent at operating pressure of 330 psig. The removal efficiencies decreased to approximately 60 percent at operating pressures of 180 psig.[12] These tests were with flat membrane in a spiral wound configuration. With the polyamide hollow fiber membranes, the fluoride removal efficiency of 40 percent at pH 5.5 was increased to 96 percent when pH of the water was at 7.0.[13] Similar improved fluoride removals have been obtained at the Fort Irwin, California, treatment plant using spiral wound membranes when the pH of source water was increased.

Several distinct reverse osmosis membranes are commercially available and have been installed in water treatment facilities. These membranes are divided into two main categories, namely,

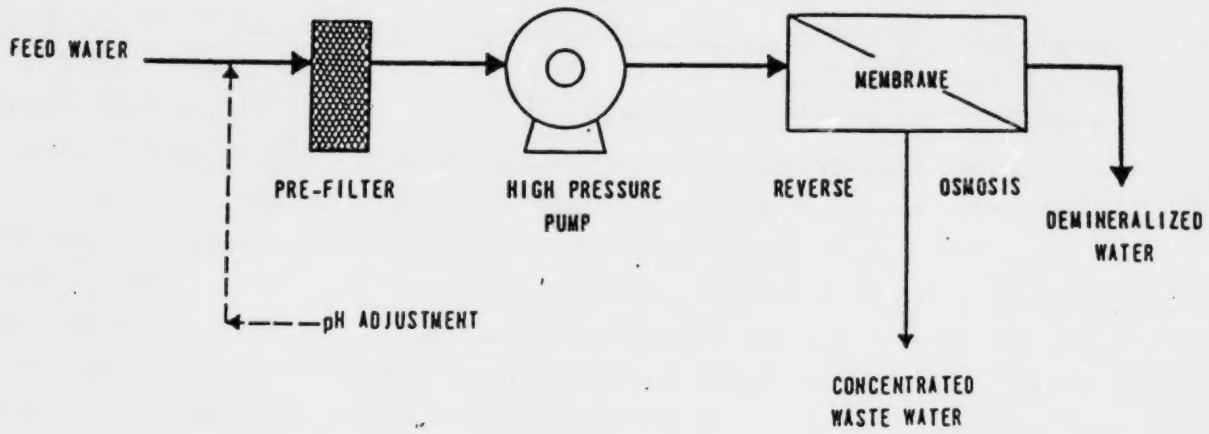


FIGURE 2 TYPICAL REVERSE OSMOSIS TREATMENT FACILITY

films in sheet form and hollow fibers. Chemically, the membranes in sheet form are either (1) cellulose acetate, (2) blends of cellulose acetate, i.e., diacetate and triacetate, or (3) thin film composites. In the hollow fiber forms there are two types: (1) polyamides and (2) triacetates. The latest development is the thin film composite membrane. These composite membranes consist of a very thin active layer of noncellulosic material, such as polyether/amide or polyether/urea, deposited on and supported by a heavier substrate sheet, such as polysulfone. The thin film composite membranes, compared to the cellulose acetate films, have broader pH range resistance and better soluble salts rejection capability. Their high salt rejection capability, 99 percent or greater, enables them to treat seawater in a single pass. However, no membrane dominates the field because of various differences in economics, performance and character of the feed water to be treated.

Engineering designs for reverse osmosis plants are governed by the need for high packing density of the active membrane area, that is, square feet of membrane area per cubic foot of pressure vessel volume. The hollow fiber by nature lends itself to high packing density, while the sheet membrane achieves good packing density through the spiral wound module. Production on a volume basis is balanced, to a degree, between the two designs, in that the fibers have a higher packing density, 5,000 sqft/cuft, but a lower flux, 2 to 4 gfd, while the spiral modules have a lower packing density, 300 sqft/cuft but a higher flux, 15 to 30 gfd. The earlier designs, namely, the tubular and plate and frame configurations, although otherwise effective in performance, could not meet the economic criteria for large municipal plants. Spiral wound modules usually can treat feed water having a turbidity of 1 turbidity unit (TU) or less. Hollow fine fiber systems require a turbidity less than 0.3 TU.

Of particular concern in water treatment is the sensitivity of the membranes to attack by free chlorine. Although all membranes have some susceptibility to attack by free chlorine,

cellulose acetate can tolerate up to 1 mg/L chlorine while the noncellulosic membranes will not tolerate chlorine.

Pretreatment criteria for feed water can have important bearing on the economics of the reverse osmosis process. The pretreatment requirements will vary depending on the physical and chemical characteristics of the water source and the presence of those substances that adhere or tend to precipitate when their concentration increases at the membrane surfaces. Reverse osmosis membranes can be fouled by calcium carbonate, iron and manganese oxides, silica, clays and microorganisms. Adjustment of the pH to approximately pH 5.5 and addition of chelating agents will help prevent scale formation.[2] The need for additional pretreatment facilities exists when the frequency of membrane maintenance becomes an operating problem.

In recent years there has been considerable developmental work directed toward producing a so-called low pressure membrane for brackish waters. That is, a membrane which operates at a pressure in the order of 200 psi and with an acceptable flux and salt rejection. These membranes would compare with the current commercial membrane operating at 400 psi. A prime advantage would be savings in energy and equipment costs. The Office of Water Research and Technology (OWRT), Department of the Interior, has been active in the development of such a membrane and has listed as its development objective a membrane operating at 250 psi with salt rejection and flux equivalent to the present day 400 psi membrane.[14] Reverse osmosis has been effective in removing total dissolved solids from seawater at operating pressures of 800 psi. Typically, higher operating pressures are required to obtain a high fluoride removal. Operating experience and cost data from 14 reverse osmosis plants, of which 11 are brackish water and 3 are seawater, were used to develop design criteria and costs.[10] All but 3 plants are for municipal use. Other requirements for reverse osmosis of a conceptual nature have been prepared by the OWRT.[15,16]

Tests are now in progress at Charlotte Harbor, Florida, to

compare cellulose acetate membranes operating at the conventional 400 psi and a low pressure cellulose acetate operating at 200 psi.[12] Fluoride removal efficiencies of 92 percent have been obtained with the high pressure membrane (400 psi) and 60 percent with the low pressure membrane (200 psi).

As the preliminary report points out, there are possibilities for trade-offs between the low and high pressure membranes. The high pressure membranes, because of their higher rejection, will offer excellent possibilities for increasing total production by blending with the feed water. Blending may not be possible with the low pressure membrane. However, if only a small amount of fluoride needs be removed to meet the MCL, then the low pressure, low rejection membrane could be adequate. Field test data of this nature are needed for future process selection and for design and feasibility studies.

Normally when reverse osmosis is to be used for fluoride removal, reduction in salinity will also be an objective and a concurrent benefit. The selection of reverse osmosis for fluoride removal may also be encouraged by the possibility of simultaneous removal of other inorganics, which may also be present, and for which the MCL's must also be met. Some water treatment systems presently operating activated alumina plants for removal of fluorides are considering replacement of the activated alumina with reverse osmosis. The reason for this is that the excessively high total dissolved solids in the product water are undesirable for consumption.

3. Lime Softening, Modified: In 1934, it was discovered that the addition of lime to fluoride spiked waters resulted in partial fluoride removal, reducing fluoride from 5.0 mg/L to 3.0 mg/L. Co-precipitation of the fluoride was found to occur when the carbonate and magnesium hardness precipitated and the phenolphthalein alkalinity was greater than or equal to the total alkalinity. Any conventional treatment process for precipitation softening employing lime, excess lime or lime-soda ash can be

utilized for fluoride removal.

During the lime softening process, calcium and magnesium ions are chemically precipitated and removed. Hydrated lime reacts with the bicarbonate ions to chemically precipitate carbonate hardness as insoluble calcium carbonate and can also react with the magnesium ions to precipitate magnesium hydroxide. Fluoride is removed as a co-precipitate with the magnesium hydroxide.

The fluoride efficiency of lime softening depends on the amount of magnesium present in the raw water. The raw water must be rich in magnesium since the removal of a small quantity of fluoride involves the removal of a large concentration of magnesium. If the magnesium needed is not naturally present, magnesium salts may be added, increasing the cost of treatment. Thus, this method would be most adaptable to low-fluoride/high-magnesium water supplies. To reduce 8 mg/L of fluoride to 1.5 mg/L, about 130 mg/L of magnesium (417 mg/L of $CaCO_3$) is required. If sufficient magnesium is not present, dolomitic lime can be used and it may provide sufficient magnesium for some waters.[17] Typically, most natural waters do not have sufficient magnesium present to remove fluoride which exceeds 3 to 4 mg/L. Excess lime softening will remove from 30 to 70 percent of the raw water fluoride along with the precipitation of magnesium hydroxide.

A detailed analysis of the mechanism of fluoride reduction during lime softening concluded that fluoride was adsorbed on the gelatinous magnesium hydroxide precipitate, formed in the lime/magnesium reaction.[18] The analysis also found a mathematical relation between magnesium and fluoride removal, which indicates that the fluoride reduction is approximately equal to seven percent of the initial fluoride multiplied by the square root of the magnesium removed. Consequently, only a high degree of magnesium removal will result in significant reductions of fluoride. Strict control of pH and caustic alkalinity must be maintained to secure proper magnesium precipitation.

Operational data of fluoride reduction by three small lime softening plants in Ohio showed fluoride removal efficiencies ranging from 44 to 53 percent.[18] These experiments with local waters showed increases in fluoride reduction when adding sufficient magnesium to a lime softening process.[19] The magnesium dosages resulted in good fluoride removals (from 3.2 mg F^-/L influent to less than 1 mg F^-/L effluent). However, scale-up calculations indicated that the additional magnesium requirement was excessive. Several plants in states with hard water wells, such as Ohio, Indiana and Illinois, were able to achieve modest fluoride levels economically because these waters contained adequate amounts of magnesium.[20] The operating costs of these softening plants were much lower than any of the more specialized processes, but the initial capital required to build such a plant was high.

There are two general classes of continuous precipitation softening equipment: (1) separate precipitation and sedimentation, and (2) solids contact reactor.

As shown on Figure 3, the separate precipitation and sedimentation technique requires equipment similar to that used for coagulation and sedimentation operations. A rapid mixer, consisting of essentially a propeller type agitator confined in a small chamber, instantaneously mixes raw water with the lime and other chemicals. Flocculation and sedimentation tanks are then used with retention periods of two and four hours, respectively.[2] To achieve recarbonation and stability, carbon dioxide or sulfuric acid is introduced into the system prior to the final filtration and chlorination.

A continuous solids contact softener has also been used with favorable results. The reactor results in the constant contact of fresh raw water with previously formed sludge. Using this system, precipitation occurs and equilibrium is quickly established. A shorter retention time affects savings in equipment cost, construction time and floor space for this method when compared with the sedimentation method. Chemical

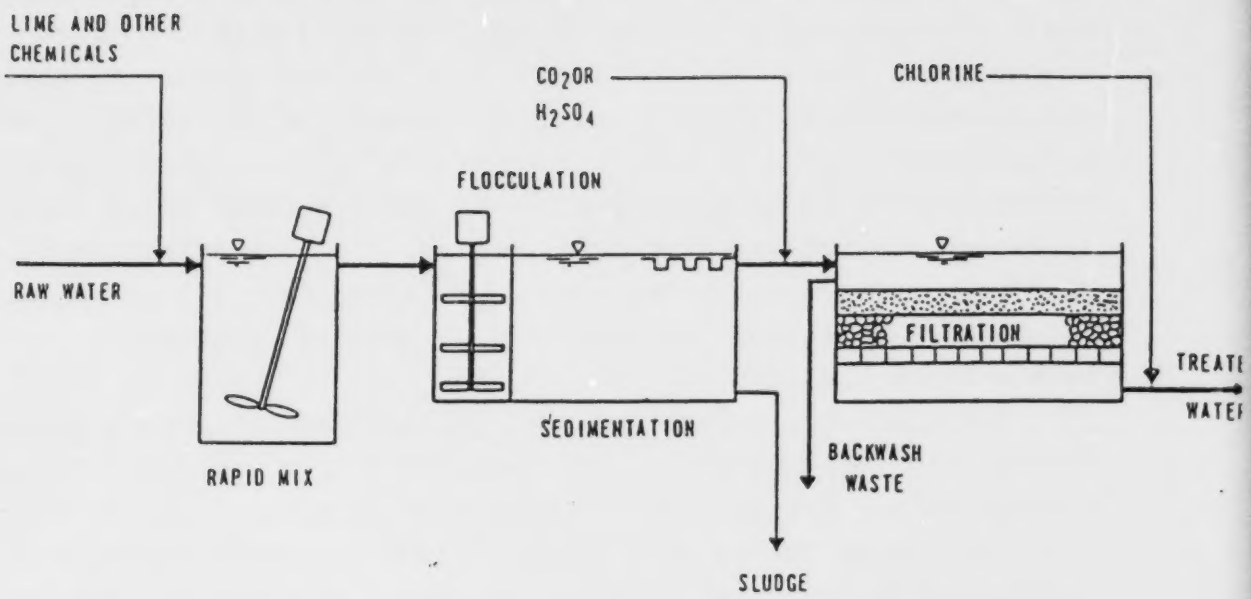


FIGURE 3 SCHEMATIC FLOW DIAGRAM OF SOFTENING

WITH PRECIPITATION AND SEDIMENTATION BASINS

requirements are also low. A minimum of maintenance and supervision is required for these systems.

Lime softening of a high fluoride raw water will require a large capital investment and high operating costs, primarily due to lime and magnesium chemical usages. Construction of a full scale softening plant for fluoride removal alone would not be cost effective unless other benefits can be derived from it.

4. Bottled Water: The bottled water industry has become one of the fastest growing and highly competitive industries in the United States. The Food and Drug Administration (FDA) has regulations that establish maximum contaminant levels for the same contaminants at the same levels as EPA's MCL's for bottled water when used in interstate commerce. In addition, FDA has water testing requirements and standards for processing and bottling of bottled drinking water.(21) Some states also control the quality of intrastate water.

Many water consumers purchase bottled water for cooking and drinking purposes without a specific water quality complaint. In 1981, bottled water sales reached 600 million gallons annually, with a cost of $588 million. Sales have been rising at a rate of 10 to 12 percent per year. California accounts for about 50 percent of the sales while Florida, Illinois, New York and Texas account for an additional 37 percent. The current industry is comprised of approximately 500 individual bottlers. Route delivery is the predominant means of distribution.(18)

Duluth, Minnesota, augmented its public water supply with bottled water in 1973. A special survey conducted to determine how the citizens of Duluth coped with the asbestos contamination of their water supply revealed that 47 percent used the contaminated tap water without further treatment, while 53 percent used alternative sources of water for potable use. Of those using alternative sources, 51 percent used specially filtered water available at public buildings throughout the city, 29 percent obtained water from wells, 6 percent used filtering

devices in the home and 6 percent used bottled water. The remaining 8 percent obtained water from other sources, such as farmers, rain barrels, and water from adjoining cities, such as Superior, Wisconsin, which had no contamination problem.[22]

Although bottled water is relatively costly, it should be remembered that this water would be used only for drinking and food preparation, which represents a small amount of the total household water use. Typically, community water use for drinking and cooking purposes is about 0.5 gallons per capita per day (gpcd).[23] The cost of bottled water is substantially reduced if only 30 percent of the households are provided with bottled water. From the 1980 census, it was determined that 30.4 percent of the families have children under 9 yars old.[24] Children under the age of 9 are considered most likely to be affected if drinking water consumed exceeds the fluoride MCL.

The methods by which bottled water is presently delivered to the household varies with different situations with the major portion of bottled water being supplied by route delivery. Vending machines for bottled water were introduced in California in 1964. Normally these machines treat a public supply by filtration, reverse osmosis, and ultraviolet radiation. The machines deliver water to the consumer's own container, thus reducing the cost substantially.

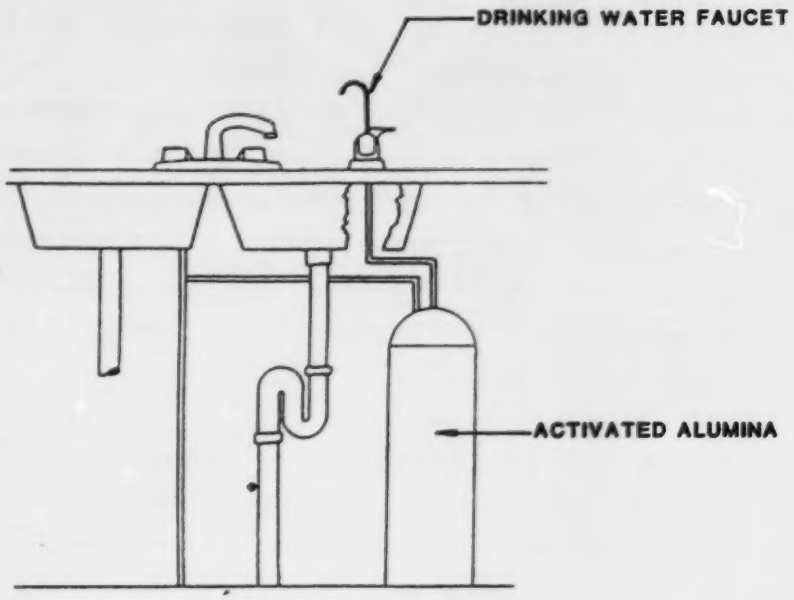
A small system utility may find it more economical to deliver bottled water door-to-door on a route basis rather than augment or install new treatment facilities to treat the entire supply. A subsidy by the utility plus a pro-rated contribution by the consumer could be anticipated.

Private bottling companies under contract to the utility could provide water and bottling facilities. Likewise, the bottled water could be delivered to the consumer under contract with the utility. A survey of over 20 private bottling companies showed that only some firms, because of the quantity of water to be delivered, would be able to serve an entire community; 90 percent indicated that they could service a community of 250

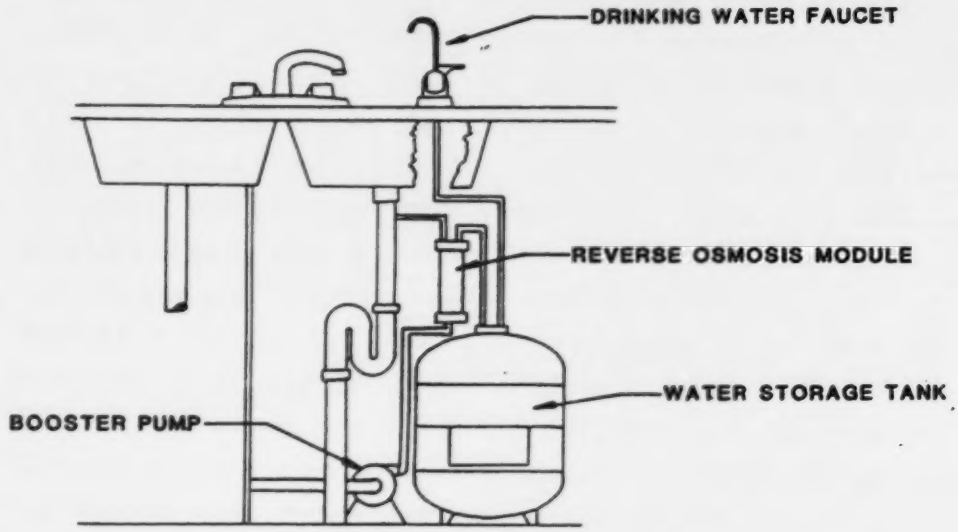
people, while only 14 percent indicated that they could service a community of over 5,000 people.[25] Where no bottling companies are available, a utility should be able to procure and deliver water at costs comparable to a local bottler. The utility would have the choice of source water to be distributed, which could range from partial treatment of the system's supply to remove the inorganics for bottling purposes, to trucking in water of acceptable quality. Utilizing a source already available to a local bottling company is another option.

5. Point-of-Use: Point-of-use treatment devices provide a technically feasible alternative to centralized treatment facilities for fluoride reduction and may be more economical for some systems than a central treatment system. The cost of point-of-use treatment is substantially reduced if installed in only 30 percent of the households. This is the percentage of families with children under 9 years old who are affected by fluoride concentrations exceeding the MCL.[24] Point-of-use treatment would be economically competitive for very small water systems where the economies of scale for the larger centralized facilities are not apparent. A major part of the attractiveness of these devices is their ability to be installed within residences. Consequently, only the water required for drinking and cooking is treated, thus reducing size and replacement requirements to a minimum. The most common technique for providing such treatment capacity is installation of a device under the kitchen sink. A simple by-pass of the existing cold water line can provide water to the point-of-use device attached to an extra kitchen faucet, such as shown in Figure 4. A second alternative is to treat all of the water delivered to a property, i.e., water for all indoor and outdoor uses. A third option is that treatment be confined to water for indoor uses only.

Point-of-use treatment has been a widely developed industry for water softening. More recently, however, home treatment units to remove a variety of water contaminants, including



ACTIVATED ALUMINA TREATMENT UNIT



REVERSE OSMOSIS TREATMENT UNIT

FIGURE 4 POINT-OF-USE DEVICES

fluorides, from the delivered water have been developed.

Both activated alumina and low pressure reverse osmosis processes are adaptable to individual family homes or, in some cases, buildings serving more than one family, or a small community. These systems require a minimum of operating controls, and can be actuated by water pressure and automated if desired. Evaluation of several point-of-use devices for fluoride removal in Illinois[9] and Arizona[2] have shown that commercial units are adaptable to household application. Experience with field operating units in New Hampshire for removal of arsenic include activated alumina and reverse osmosis devices.[26]

The capital costs associated with the removal of fluoride from drinking water would be borne by the community water utility where it was considered that such a treatment system is feasible and cost effective. The utility could install and service the units or contract with a local water service company to perform the installation and servicing. Operating and maintenance (O&M) costs are important factors in the point-of-use treatment method and the problems incumbent from the logistics of managing and maintaining a decentralized system, along with extra monitoring costs, could mitigate against a point-of-use approach. However, when operating and maintenance costs are not excessive, some small community water systems may find this alternative treatment both feasible and cost effective.

a. Activated Alumina: Recently, activated alumina has been installed in home treatment units to evaluate the effectivness of this material on a small-scale application. Several studies of these units are underway. Although the units utilized to date were not specifically designed for activated alumina, several water service companies are in the process of manufacturing such units. Service at intervals depends on water quality, quantity and the influent fluoride concentration.[27]

Although large-scale production of home activated alumina systems has not yet occurred, it appears a major water service

company is in the process of producing such a system. Other service companies have utilized existing granular activated carbon (GAC) contactors as the vessel to contain the activated alumina. Since drinking and cooking water uses would be the only exposure vehicle, a small cylinder containing activated alumina could be installed inside or outside the home and connected to the water supply into the kitchen using a new water tap. Activated alumina must be periodically regenerated based on fluoride content of the feed water. Although in-place regeneration is possible, it would be preferable to replace the cylinder with a new or regenerated unit after a definite period based on calculations of the volume of water passed through the cylinder and its fluoride content. A central servicing location could be used to regenerate the spent media.

b. Reverse Osmosis: Home reverse osmosis (RO) treatment units currently are available in under-the-counter units to treat a portion of the delivered water or in full scale treatment units serving apartment complexes. Several manufacturers are available to ensure competitive capital costs and strong warranties. The smaller RO units can effectively treat up to 5 gallons per day using normal system pressures. For larger capacities, booster pumps will be required to increase the operating pressure across the RO membrane. Servicing is dependent on water quality and quantity used, at which time the membrane might be chemically cleaned or replaced. With reverse osmosis the replacement of membranes will be less time consuming and less complex than regeneration of activated alumina. Reverse osmosis also provides other water quality benefits, such as the reduction of salinity and hardness and the removal of other inorganic contaminants that may be present, along with the fluoride. The water utility will be required to perform routine sampling and laboratory testing to ensure compliance with the MCL requirement.

Several point-of-use reverse osmosis manufacturers have developed and marketed small scale RO units suitable for in-home

use. Dealerships have typically been set up around the country to ensure the proper installation and servicing of these units.

6. Regionalization: A feasible option, especially for small water systems that are out of compliance with the fluoride MCL requirements, is to join with other small or large systems that do comply with MCL requirements to form a regional water supply system. A schematic of such a system is shown in Figure 5. Regionalization provides a feasible mechanism for resolving MCL compliance problems. An alternative is to install additional treatment methods to meet the MCL, resulting in cost increases. Installation, operation and maintenance of additional control processes, together with monitoring requirements, all result in an increase of cost of the product to the consumer. Examination of these costs and impact could influence a water system to consider regionalization.

Generally it is the smaller communities or systems that encounter fluoride concentrations in excess of the MCL. The small systems also tend to have more operational reliability problems than do the larger systems. In addition, there may be other advantages, such as shared maintenance service and/or central billing, which show economies of scale.

The availability of an acceptable and adequate water supply and its distance from the affected system are important cost factors that a system must examine when making a choice between regionalization or maintaining its own treatment system.

Regionalization provides small water systems that do not comply with MCL requirements the option of joining with other smaller utilities or a large utility to form a regional water supply system.

7. Alternate Source: Development of alternative water sources located within a reasonable distance of a community which do not exceed the MCL for fluoride contamination may provide a satisfactory solution to a community water quality problem.

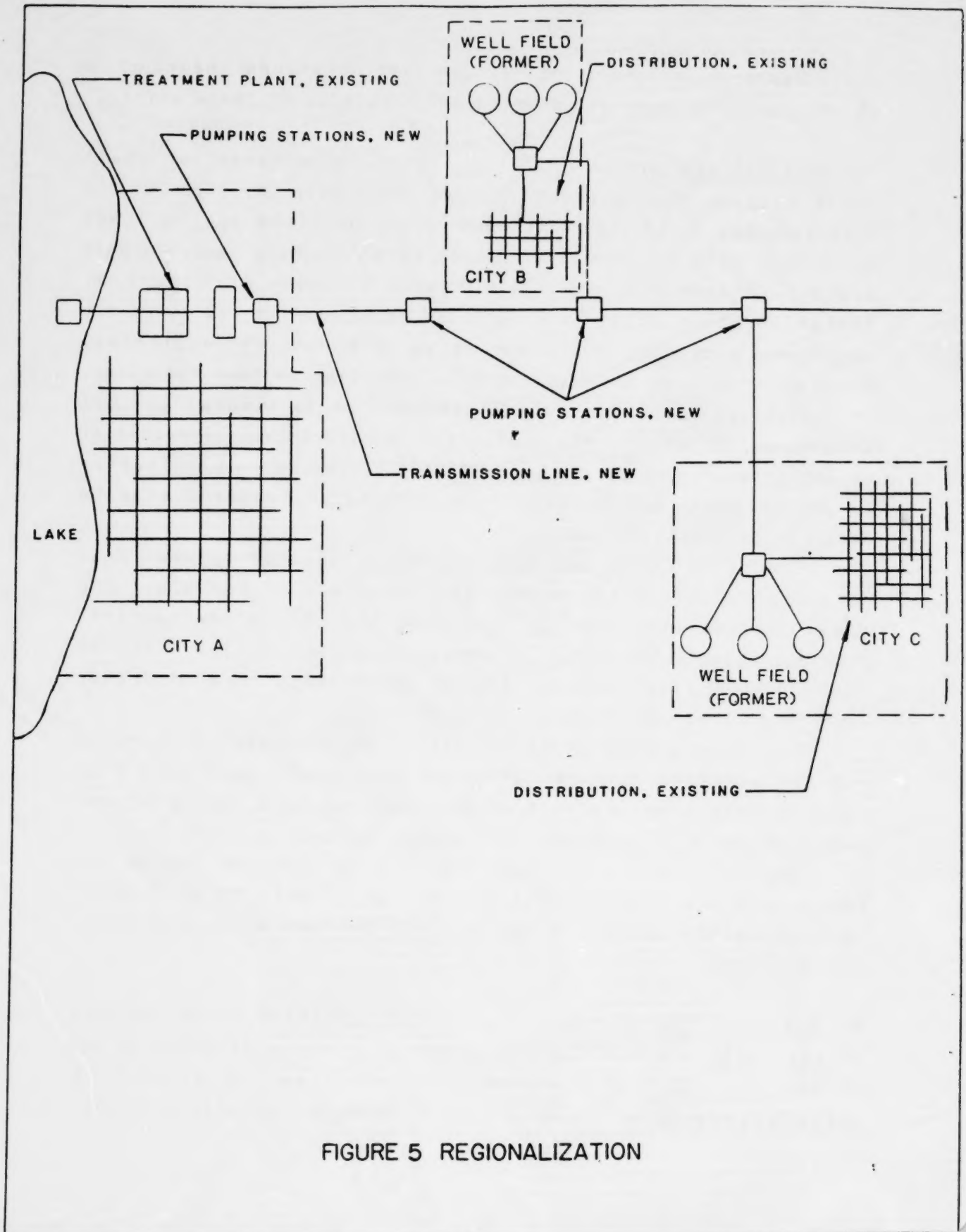


FIGURE 5 REGIONALIZATION

Since the majority of the systems with fluoride exceeding the MCL are from groundwater sources, available surface water sources are likely options as alternate sources. Although the surface sources may contain less fluoride, they may require treatment, such as clarification and disinfection, which may be as expensive as removing fluoride from the original source water. Furthermore, fluoride in the original source may vary with the hydrologic and geologic conditions in the area and developing wells of different depths and at different locations should not be precluded. In any event, alternate surface water or groundwater sources may be available depending upon the size and location of the system and the costs involved. A schematic of an alternate source application is shown in Figure 6, where a community with high fluoride concentrations in its groundwater supply selects an adjacent surface water source which meets the fluoride MCL requirement.

Many communities may have existing facilities that can be utilized in the development of an alternative source. For example, systems with filtration or chlorination processes may adapt existing processes to treatment of a new water source. Different combinations of new and existing processes relative to size of the system and quality of water source impact significantly on cost and complexity.

An alternative raw water source of superior quality may be available to a community water system for reducing and/or eliminating the need for an existing high fluoride water source. Either a surface water or a new groundwater source may be available depending upon the size and location of the system.

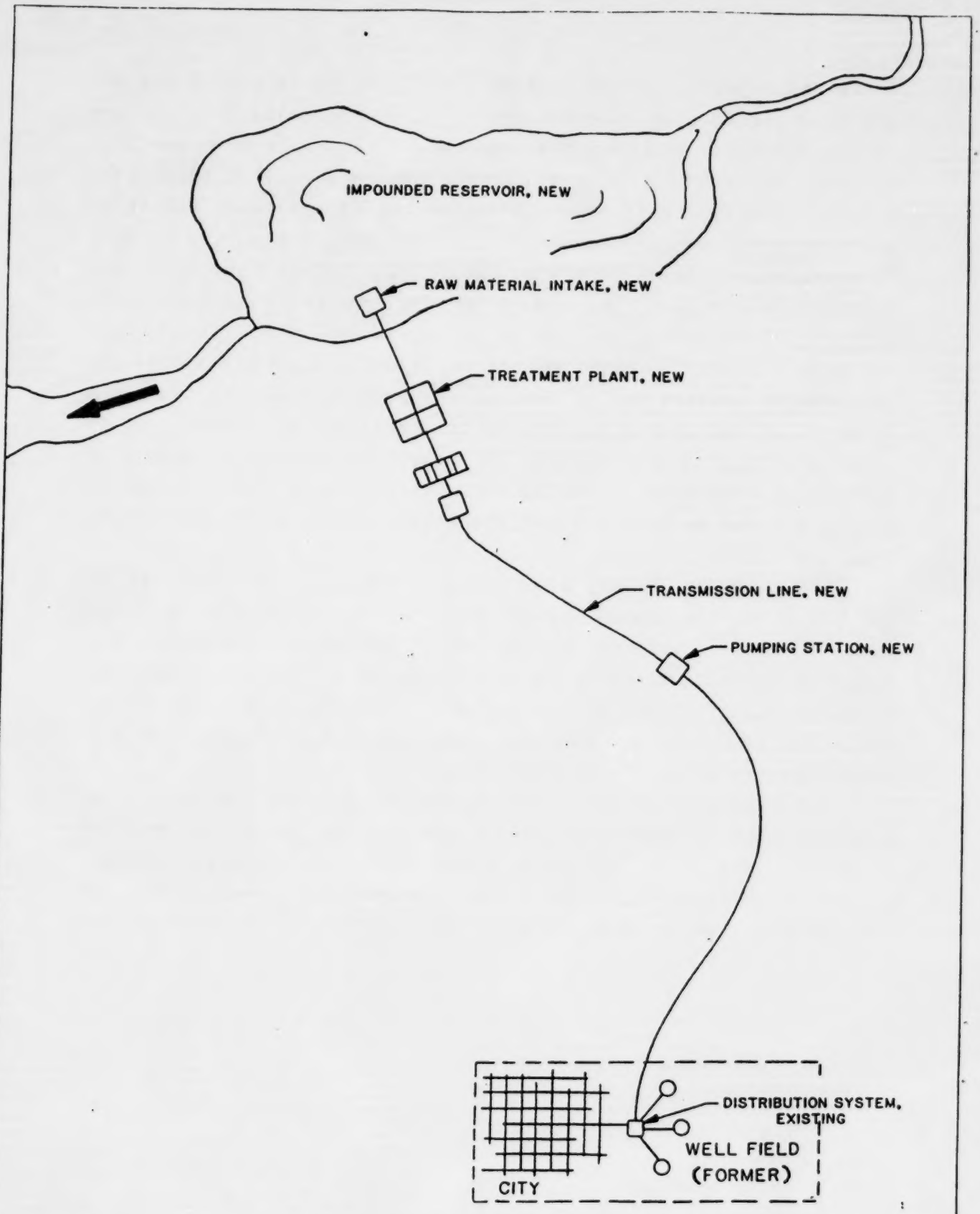


FIGURE 6 ALTERNATE SOURCE

EXPERIMENTAL TECHNOLOGIES WITH POTENTIAL FOR REDUCING FLUORIDES IN WATER

Technologies have been identified which have shown potential use in removing inorganics from water and, with verification of satisfactory fluoride removal efficiency, should be considered for specific situations. The methods identified are:

1. BONE CHAR.
2. TRICALCIUM PHOSPHATE (SYNTHETIC BONE CHAR).
3. RESINS (ANION EXCHANGE).
4. ELECTRODIALYSIS.

Discussion of Other Technologies

1. Bone Char: The use of bone for defluoridating water was the earliest reported treatment technique shown to be effective. However, bone char was found to impart an undesirable taste to the water and was of high cost. Subsequently, it was found that bone char could be substituted at a more economical cost and that there are no undesirable taste problems from its use. Bone char is produced by charring animal bones to remove the organics.

New bone char has an adsorption capacity of about 500 to 700 grains/cuft, which is reduced to about 200 grains/cuft following repeated use. The capacity also appears to decrease with lower influent fluoride levels. After exhaustion, bone char can be regenerated using caustic soda followed by an acid rinse.

Bone char is soluble in acid; therefore, a pH of around 7.0 is recommended to prevent loss of media and optimize fluoride removal. The presence of chloride ion increases the exchange capacity. Also, hardness ions, specifically magnesium and calcium, enhance fluoride removal when using bone char media.(2)

The use of bone char as a defluoridation medium is not

practical for waters that contain arsenic, because arsenic causes irreversible changes in the composition of the bone char. Water that has a very high TDS can be treated effectively with bone char. Highly alkaline waters have a lower effluent pH when treated with bone char than when treated with activated alumina.

One of the first full scale defluoridation plants to use bone char as the exchange media was located in Britton, South Dakota. This plant, operated from 1953 to 1971, was a pressure type facility with the media in an enclosed steel contact tank, which contained 300 cuft of 28 to 48 mesh size media.[5] A caustic soda dilution tank and acid solution apparatus were also utilized. Water was pumped through the contact tank at rates varying between 38 and 206 gpm. The fluoride concentration was reduced from 8 mg/L to 1 mg/L, with about 450,000 gallons being treated between regenerations.[2] A total of 6,500 gallons of treated water and 28,000 gallons of raw water were used in regeneration. Media capacity with 8 mg/L fluoride water was 700 grains/cuft.(2,5)

At a plant constructed in Fort Irwin, California, in 1954. the same type of equipment described above was used to treat a water with influent fluoride levels ranging from 9 to 12 mg/L. Two defluoridation units were operated in parallel, each with the capacity of treating 33 gpm.[2,5,7] Regeneration was accomplished using sodium hydroxide (NaOH) and phosphoric acid (H_3PO_4). The use of phosphoric acid to regenerate the media caused replacement of the media in one year. The finished water contained an average of 0.6 mg/L fluoride. A schematic diagram of a two-contactor bone char treatment facilitiy is shown as Figure 7.

In order for a full scale bone char treatment facility for fluoride removal to be effective, an improved and more cost-efficient supply of bone char is needed.

2. Tricalcium Phosphate (Synthetic Bone Char): Tricalcium phosphate is formed by reacting phosphoric acid and lime. Unlike

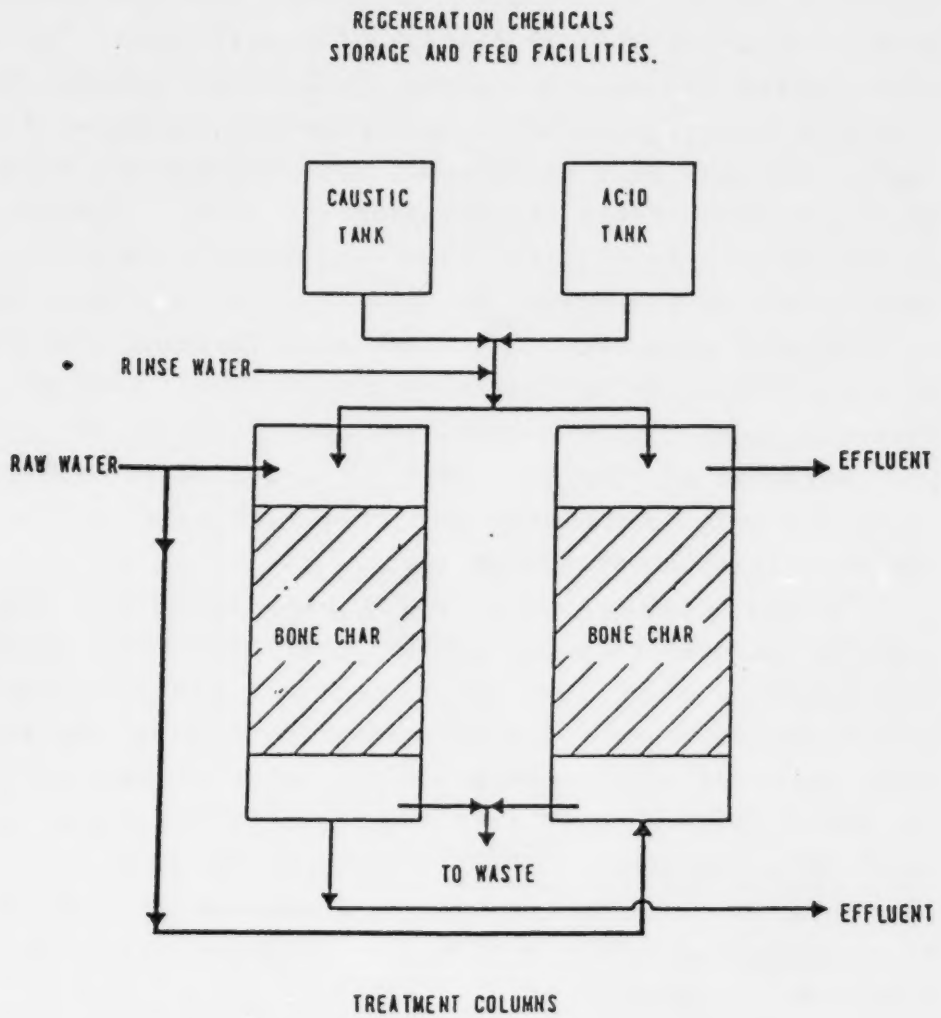


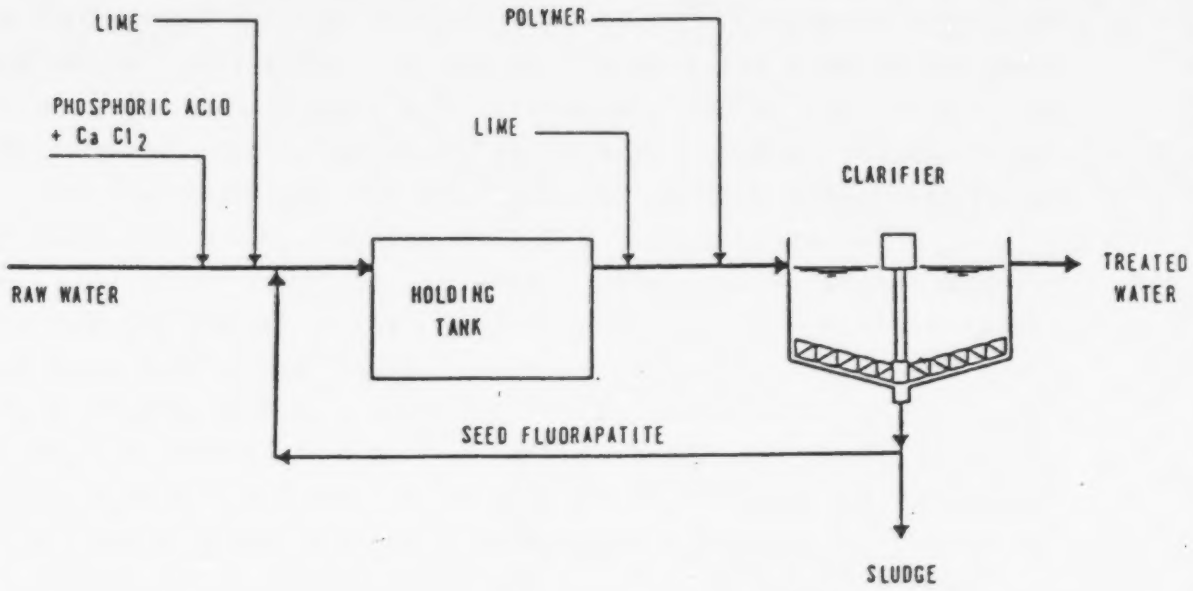
FIGURE 7 SCHEMATIC OF BONE CHAR PROCESS

natural bone char, the exchange capacity of tricalcium phosphate is not significantly affected by a change in the raw water pH or fluoride level.[28] Both granular and powdered forms of tricalcium phosphate are commercially available. Two plants were constructed [Climax, Colorado (1938) and Scooba, Mississippi (1940)] using granular tricalcium and operated for about 10 years, and then were abandoned. This process was also installed at the Britton, South Dakota, plant in 1948. Although this media proved to be effective for fluoride removal, excessive attrition losses were experienced. Because of this, the media was replaced in 1953 with bone char.[2] Granular tricalcium phosphate is not an available fluoride treatment alternative. However, a powdered form has been tested which removes fluoride through chemical precipitation of fluorapatite.[2,5] Full scale evaluations will be required to determine the availability of the precipitative use of tricalcium phosphate.

A prepackaged system has been developed that provides fluoride removal through chemical precipitation. Phosphoric acid and calcium chloride are mixed and added to the raw water containing fluoride. The acid addition lowers the pH. Lime is then added to adjust the pH of the water to between 6.2 and 7.0. The water is mixed with seed fluorapatite and kept in a holding tank for seven minutes.[2] From here the solution is fed to a clarifier after another in-line injection of lime to adjust the pH to between 7.5 and 9.5. A polymer also is added as a flocculation agent at this point.

After clarification, the effluent water has a fluoride concentration of less than 0.5 mg/L. Excess sludge not returned to the system as seed fluorapatite can be disposed at a landfill. Most sizes of this process are prepackaged plants and require only terminal connections before starting operation. A schematic of this process is provided on Figure 8.

Granular forms of tricalcium phosphate have previously been evaluated on plant scale basis and found not cost effective for fluoride removal. On the other hand, the application of a



NOTE: ANDCO SYSTEM

FIGURE 8 SCHEMATIC OF TRICALCIUM PHOSPHATE FACILITY

powdered form of this media appears promising; however, additional testing and full scale evaluations are necessary to determine design criteria and costs.

3. Resins (Anion Exchange): Strong-base anion exchange resins in the chloride form have been evaluated for efficiency of fluoride removal.[29] The efficiency of the media has been observed to be a function of the ratio of fluorides to the amount of total anions in the raw water. The fluoride capacity of these resins is 100 to 400 grains F^-/cuft, which is well below that of other exchange media. Because of low capacity due to other anions in the water supply and high resin cost, other treatment methods should be evaluated. However, if other anions need to be removed, strong-base anion exchange resins should be evaluated since they have advantages over activated alumina and bone char.

Strong-base anion exchange resins have a relatively low exchange capacity for fluoride and will depend on the ratio of the amount of fluoride to the amount of the total anions in the raw water. A schematic diagram of a typical ion exchange process is shown on Figure 9.

4. Electrodialysis: The electrodialysis process has been used for demineralization of brackish waters since 1965.[2] This process removes ionized salts and minerals from water by the migration of ions through ion-transfer membranes, under the influence of a direct-current electrical field. This process, however, will not remove colloidal matter, nonionized matter or bacteria.

The cost of demineralization is directly proportional to the amount of salt required to be removed since the amount of electric current required varies directly with the number of ions transported.

For optimum operation, electrodialysis plants require clear waters, free of iron, manganese, turbidity and organic matter. Problems associated with the electrodialysis process include

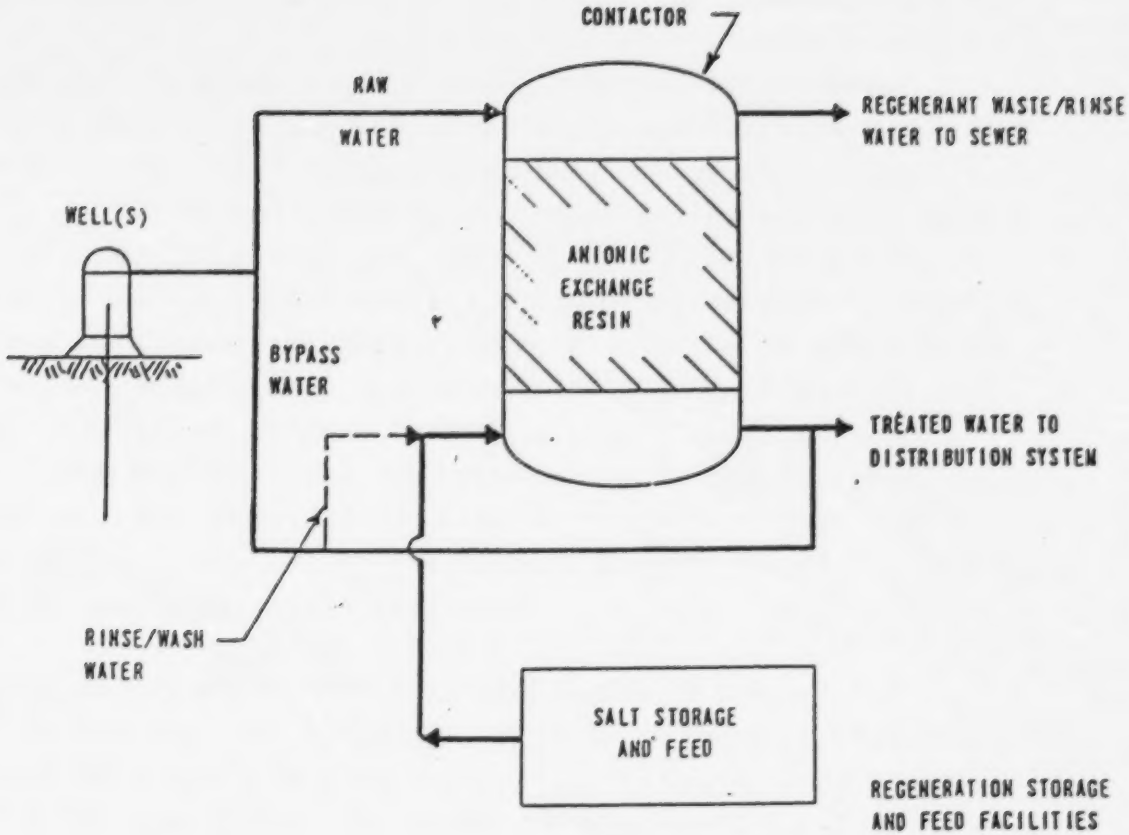


FIGURE 9 SCHEMATIC OF ION EXCHANGE PROCESS

chemical precipitation of salts with low solubility on the membrane surface and clogging of the membrane by colloidal organic matter. Pretreatment by conventional means is sometimes required prior to electrodialysis treatment in plants operating on groundwaters, and is always required prior to electrodialysis in plants operating on surface water.

Softening of the feed water either through lime addition, lime/soda softening, or ion exchange may be necessary to control calcium sulfate scale. Acid addition to lower the pH of the feed water will reduce the formation of this kind of scale.

Electrodialysis membranes are sensitive to chlorine and begin to degrade at chlorine residuals over 0.1 mg/L. Since the selectivity of electrodialysis is poor and essentially all ions are passed through the membranes, this process would not be practical only for fluoride removal, but could be used on water supplies requiring the removal of other contaminants. Results for the electrodialysis plants at Buckeye, Arizona, and Dell City, Texas, indicate that fluoride is removed by electrodialysis, but in a lesser percentage than the reduction in TDS.[30,31]

The amount of waste flow will have an impact on costs, both from the standpoint of waste disposal and the amount of feed water capacity that must be provided. For electrodialysis plants, the percentage of water recovery may vary from 44 percent[30] to 80 percent, with an average in the order of 70 percent. The limiting factor in water recovery is primarily the solubility limits of slightly soluble salts, such as calcium sulfate.

Electrodialysis equipment can be supplied as a package plant. The most widely installed plants today utilize the reversal modification which reverses the directions of ion flows at a periodic interval, thereby minimizing scaling of the membranes.

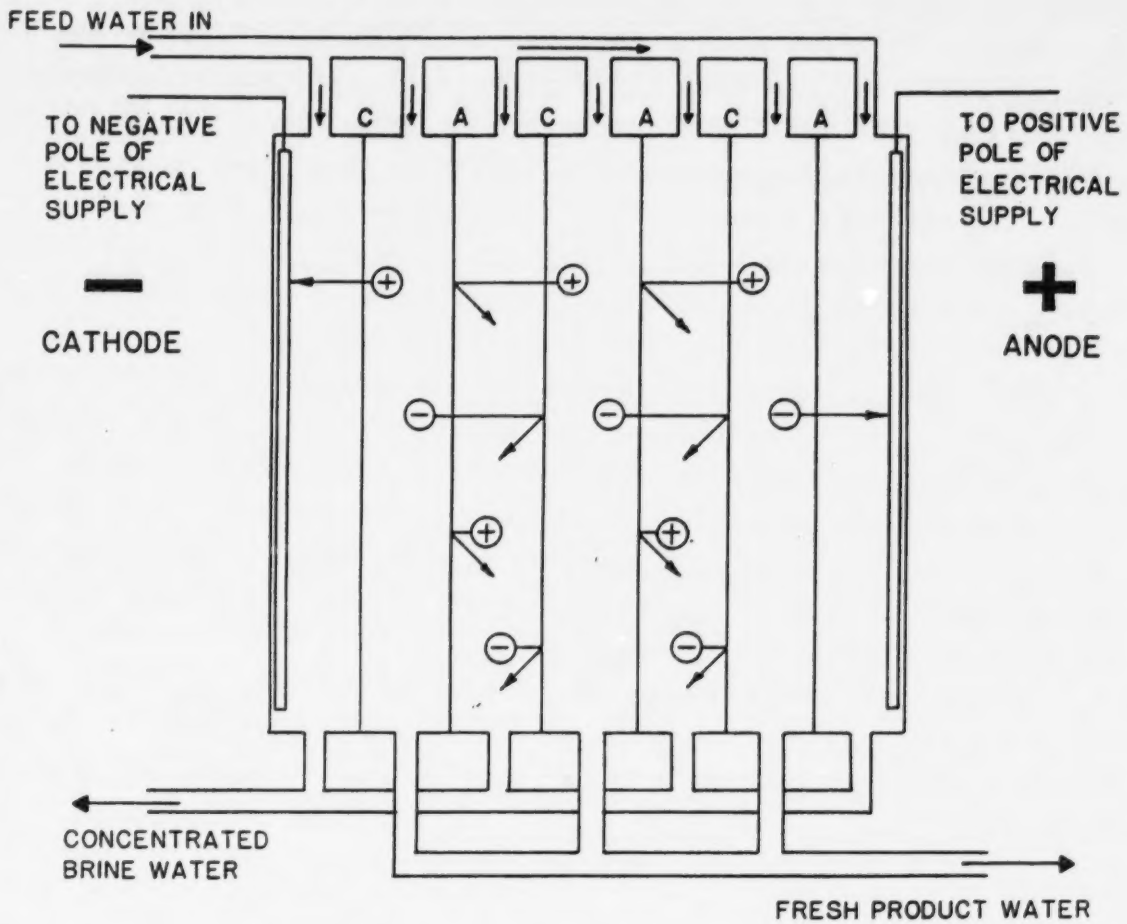
Electrodialysis plants have three main components: rectifiers, control and switching center, and the membrane stack.

The rectifiers supply the direct current required for the stacks. The control and switching centers generally enable completely automatic operation with only minimum operator attention.

Figure 10 shows a cross section of an electrodialysis stack. The positive ions can move through the cation permeable membranes toward the left until they encounter an anion permeable membrane which will not pass cations. The negative ions move toward the right through the anion permeable membranes until they encounter a cation permeable membrane through which they cannot pass. This would leave cells 2, 4 and 6 relatively free of ions and cells 1, 3, 5 and 7 would have the ions concentrated in them.

The extent of demineralization obtained in the diluting compartments will depend upon the amount of electrical current passed, the concentration of ions in the feed solution and the flow rate of the feed solution through the equipment. The amount of electrical current and membrane surface required to demineralize a given quantity of water depends upon the amount and type of mineral to be removed.

Since the selectivity of electrodialysis is poor and essentially all ions are passed through the membranes, this process would not be practical for fluoride removal only. However, electrodialysis could be used on water supplies requiring the removal of other contaminants.



LEGEND

C CATION PERMEABLE MEMBRANE

A ANION PERMEABLE MEMBRANE

⊕ CATION

⊖ ANION

FIGURE 10 CROSS-SECTION OF ELECTRODIALYSIS PROCESS

COSTS OF FLUORIDE CONTROL

Capital and operating costs for the technologies developed in this analysis were established based upon inputs, reviews and discussions with staff members from EPA Office of Drinking Water (ODW), EPA Municipal Environmental Research Laboratory (MERL) engineer consultants, actual experiences and equipment manufacturers. The costs for new systems designed for capacities in excess of 1.0 mgd were determined from equations developed by MERL[32] using the computer model written for EPA by Culp/Wesner/Culp and presented in EPA publications EPA-600/2-79-162a,[33] EPA-600/2-79-162b[34] and EPA-600/2-79-162c,[35] Estimating Water Treatment Costs, volumes 1, 2 and 3. The costs for new systems designed for capacities smaller than 1.0 mgd were developed through a coordinated effort involving EPA and several engineering firms actively working with technologies for drinking water. Much of this cost information was obtained from on-going studies, data banks, visitation of actual installations and personal contact with equipment manufacturers, design engineers and construction firms. Various parameters and calculations used in developing the costs for bottled water, point-of-use, regionalization, and alternate source are summarized in Appendix C.

All capital costs are presented as costs per year updated to 1982 dollars using the Engineering News-Record (ENR) average of the annual Construction Cost Index (CCI) for 20 U.S. cities.[36] Operating costs are based upon a Producer Price Index (PPI) for 1982 dollars. Other general cost considerations are listed in Table 1. For the purpose of estimating costs per 1,000 gallons, the capital costs were amortized over 20 years at a 12 percent interest rate. Costs for acquiring new land for construction sites or easements for a raw water transmission line are not included since these costs are extremely site specific; however, these costs, when included, would be a significant factor.

TABLE 1
GENERAL ASSUMPTIONS FOR USE IN
DEVELOPING COSTS FOR FLUORIDE REMOVAL*
(Mid-1982 Dollars)

Electric Power	$ 0.07 Kwh
Labor - Small Systems (<150,000 gpd)	$ 4.55/hr
Large Systems (≥150,000 gpd)	$11.00/hr
Diesel Fuel	$ 1.00/gal
Natural Gas	$ 0.004/scf
CCI Index	356
PPI Index	280
Sitework	15% of construction costs
Contractor's Overhead & Profit	12% of construction costs (including sitework)
Contingencies	15% of construction costs
Engineering & Technical Fee	15% of construction costs (including sitework & contractor's O&P)
Interest Rate	12%
Number of Years	20

CHEMICAL COSTS

Alum, Dry	$235/ton
Liquid Alum	$255/ton
Lime (quick lime)	$31.25/ton
Lime (slaked lime)	$32.50/ton
Ferric Chloride	$176/ton
Ferrous Sulfate	$115/ton
Ferric Sulfate	$118/ton
Soda Ash (light)	$150/ton
Sodium Hydroxide	$520/ton
Chlorine (liquid)	$145/ton
Sodium Hypochlorite (14% Cl_2)	$0.82/lb.
Calcium Hypochlorite	$94.50/100 lb. drum
Polyelectrolyte	$2.00/lb.
Liquid Carbon Dioxide	$0.05/lb.
Sodium Hexametaphosphate	$0.32/lb.
Bi-metallic Phosphate	$1.80/lb.
Aqua Ammonia	$210/ton
Sulfuric Acid (66° Baume)	$80/ton
Hydrochloric Acid	$70/ton
Powdered Activated Carbon	$0.35/lb.
Granular Activated Carbon	$1.00/lb.
Anion Exchange Resin (Strong Base)	$170/cuft
Cation Exchange Resin (Strong Acid)	$65/cuft
Activated Alumina	$30//cuft
Salt	$50/ton
Potassium Permanganate	$3.62/lb.
Sodium Bisulfite	$0.05/lb.
Sodium Silicate	$0.17/lb.

* Site specific circumstances may result in considerable variations from the costs encountered by typical systems.

See Appendix D for English/Metric Conversion.

For all the fluoride removal treatment technologies considered in this document, design and unit costs should be viewed as preliminary to be used only for planning purposes. More complete and detailed designs and cost estimates should be developed based upon pilot-plant testing and site-specific considerations.

In this analysis, wastewater disposal for all technologies was discharged to a sanitary sewer and estimated as an additional operating cost. In some locations, sanitary sewers may not be available or not be acceptable, and other more expensive wastewater disposal methods would be required. Wastewater disposal could be an important factor in determining the feasibility of treatment for some systems.

Cost estimates for the technologies identified have been developed based on the information presented above. Costs were not developed for technologies identified as having future potential because additional testing and full scale evaluations are necessary to determine design criteria and costs. The following cost estimates have been developed:

1. Activated Alumina.
2. Reverse Osmosis.
3. Lime Softening, Modified.
4. Bottled Water.
5. Point-of-Use.
   a. Activated Alumina.
   b. Reverse Osmosis.
6. Regionalization.
7. Alternate Source.

1. Activated Alumina: For the purpose of developing preliminary activated alumina cost estimates, the following assumptions were utilized:

- Minimum of two contactors, each capable of handling design flow. Contactors are steel with interior protective lining, provided with activated alumina media 5 feet deep with added height for not less than 50 percent expansion. Gravel layer surrounding underdrain. Working pressure 100 pounds per square inch (psi).
- Raw water input rate is 5.0 gpm/sqft. Backwash with raw water at 8.0 gpm/sqft for 10 minutes; upflow regeneration with 1 percent NaOH (by weight) at 2.5 gpm/sqft for 35 minutes; upflow rinse with raw water at 5.0 gpm/sqft for 30 minutes; downflow regeneration with 1 percent NaOH at 2.5 gpm/sqft for 35 minutes.
- Four percent of raw water is used for regeneration, neutralization and backwash purposes.
- Downflow neutralization with raw water at 5.0 gpm/sqft with 0.5 N sulfuric acid added by a metering pump from an acid storage tank. Approximately 0.15 pounds of 66° Baume sulfuric acid required to treat 1,000 gallons of water.
- Approximately 0.5 pounds of 50 percent liquid NaOH required to treat 1,000 gallons of water. For systems smaller than 1.0 mgd, the liquid NaOH storage tank is outside the building. For larger size systems, a 30-day supply of flake NaOH is provided and stored inside the building. Mixer, tank and metering pump are provided for the flake NaOH addition.
- Raw water pH is 7.0 and is not adjusted in operating cycle with alkalinity at <50 mg/L as $CaCO_3$. When necessary to adjust raw water pH at 5.5, based on a carbonate alkalinity of 100 mg/L, raw water is neutralized with 0.83 pounds of sulfuric acid/1,000 gallons of water.

- Capacity of activated alumina is 1,000 grains/cuft at raw water pH of 7.0 and 8 percent of bed volume is replaced annually. At raw water pH of 5.5, activated alumina capacity is 2,000 grains/cuft and 15 percent of bed is replaced annually.
- Raw water fluoride content is 3.2 mg/L and 60 percent of treated water is blended with 40 percent of raw water to maintain a fluoride final effluent of 2.0 mg/L.
- All facilities are inside a building with exception of liquid chemical storage tanks for systems smaller than 1.0 mgd.
- No costs included for heating liquid NaOH in storage.
- No costs included for raw water pumping or product water pumping.
- Electrical energy costs for building, heating, lighting and ventilation, and process energy for chemical mixing and pumping. Housing energy costs are 70 Kwh/sqft/year.
- Systems smaller than 1.0 mgd are operated 16 hours/day; larger systems are operated 24 hours/day. Operational labor varies with the size of the system. The minimum labor is 2 hours/day plus additional time for major maintenance and activated alumina replacement.
- Costs include regeneration wastewater disposal to sanitary sewer. On-site treatment of the regeneration wastewaters may be required at some locations and will result in higher capital costs.

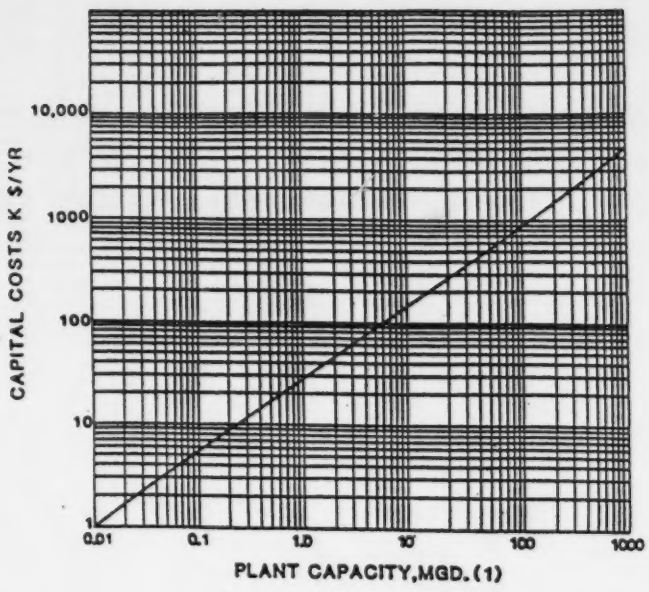
The unit processes used to estimate low range and high range costs for removal of fluorides with activated alumina are shown in Table 2. Many site specific factors will affect these costs, however in this analysis the exchange capacity of activated alumina and its relationship to the pH of the source water is used as a site specific factor for estimating the low and high range costs. The low range costs represent a system with a source water pH of 7.0 and with no further pH adjustment, and the

TABLE 2
PROCESSES USED TO DETERMINE COSTS OF
ACTIVATED ALUMINA FOR FLUORIDE REMOVAL

Low Cost Range		High Cost Range
X	Activated alumina facility* for 1000 grains/cuft	
	Activated alumina facility* for 2000 grains/cuft	X
	pH adjustment of raw water	X
	pH adjustment of product water	X
X	Wastewater to sewer	X

* Includes housing, instrumentation, piping, valves and electrical controls.

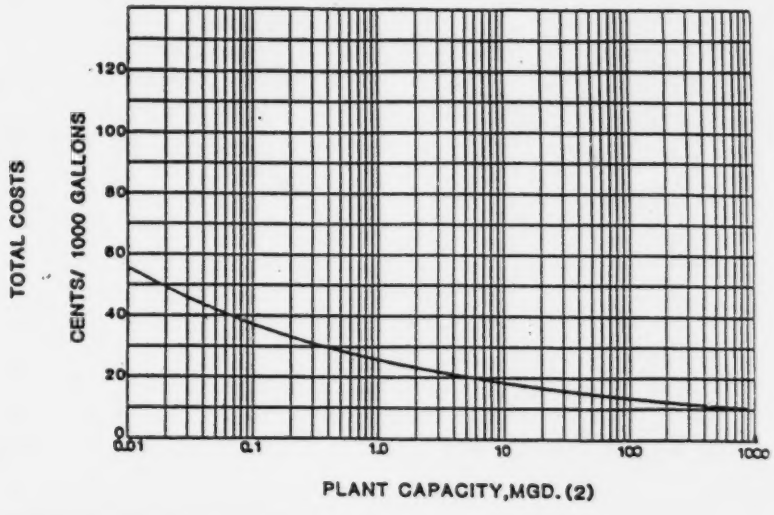
high range costs represent a system with adjustment of the raw feed water pH to 5.5. The cost estimates for various plant capacities shown in Figure 11 are average costs of the low and high range systems.



NOTE:

(1) DESIGN CAPACITY OF THE PLANT USED IN CAPITAL COST ESTIMATES.

(2) WATER PRODUCTION CAPACITY OF THE PLANT USED IN O&M AND TOTAL COST ESTIMATES.



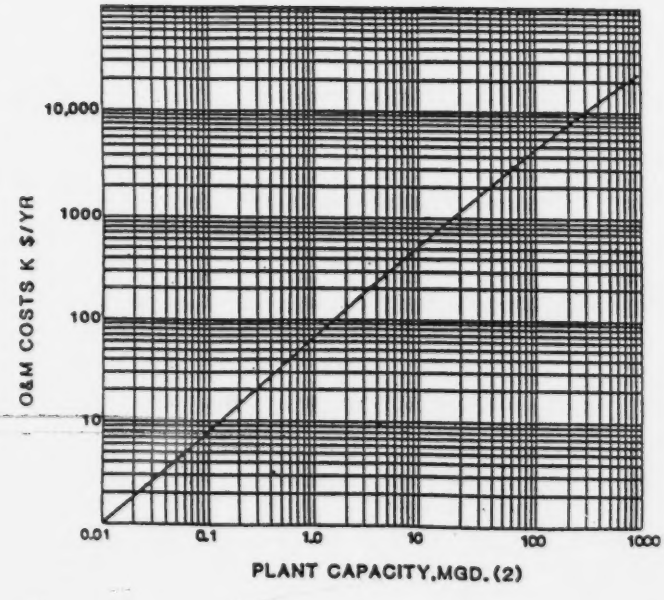


FIGURE 11

TREATMENT COSTS FOR FLUORIDE REMOVAL BY ACTIVATED ALUMINA (60/40 BLEND)

2. Reverse Osmosis: Preliminary costs estimated for the reverse osmosis treatment technology were prepared using the following assumptions:

- To maintain an optimum product water fluoride concentration, 50 percent of the RO treated water is blended with 50 percent of the raw water.
- Spiral wound or hollow fiber membranes are used and are capable of treating raw water with TDS of 5,000 mg/L in a single pass at 400 psi with a water recovery rate of 75 percent and water temperature of 25°C.
- Facility includes all treatment equipment, structural steel and metalwork, tanks, piping, valves, high pressure pump, reverse osmosis membranes and pressure vessels, membrane cleaning equipment, cartridge filters, chemical metering pumps for acid and sodium hexametaphosphate, and degasifier.
- Reverse osmosis equipment with controls and instrumentation panel are skid mounted units or multiples of such units.
- Brackish water cellulose acetate or polyamide membranes provide 93 percent salt rejection.
- Pretreatment, when added, includes multimedia filtration at 5.0 gpm/sqft with cationic polyelectrolyte continuously added to feed water at a rate of 0.2 mg/L.
- For systems greater than 1.0 mgd capacity, separate filter backwash pumping facilities are provided.
- Pumping equipment for raw water and product water are not included.
- Degasifier equipment located outside of the building.
- Electrical energy for building heating, lighting and ventilation is 70 Kwh/sqft. Process energy for high pressure pump is at 60 percent pump efficiency and process energy for the degasifier is 10 percent of the high pressure pump.

- Labor varies with size of the system with a minimum of 1 man-hour/day for the smallest system. Minimum lighting is 2 hours/day.
- Reverse osmosis membrane cleaning cycle is every 6 months. Anticipated 3 year operating life for membranes.
- Sodium hexametaphosphate fed continuously at a rate of 5 mg/L and sulfuric acid at a rate of 100 mg/L for inhibiting scale deposition on membrane surface.
- Cartridge filters replaced every 6 weeks are operated at 1.5 gpm/sqft.

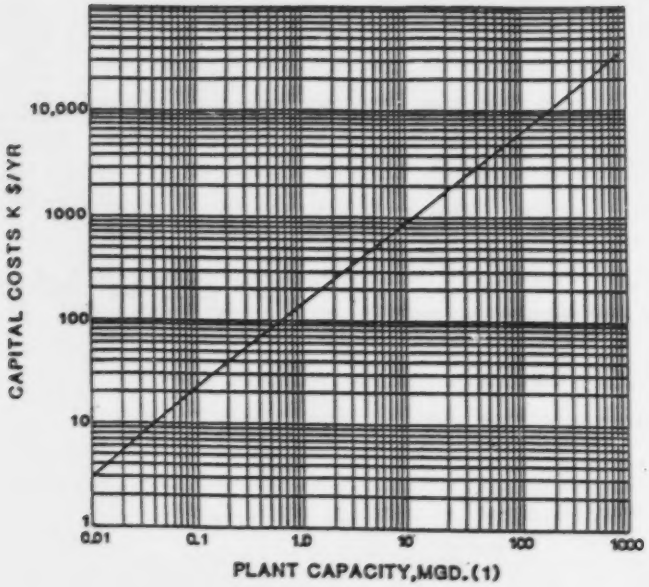
The unit processes used to estimate low range and high range costs for removal of fluoride by reverse osmosis are shown in Table 3. Many site specific factors will affect these costs. However, in this analysis the quality of the water source and requirements for pretreatment of the water are used as the site specific factors for estimating the low and high range costs. The low range costs represent a clean water source that requires no pre-clarification processes, and the high range costs represent a turbid water source and the need for pretreatment equipment. The cost estimates for various plant capacities shown in Figure 12 are average costs of the low and high range systems.

TABLE 3

PROCESSES USED TO DETERMINE COSTS OF
REVERSE OSMOSIS FOR FLUORIDE REMOVAL

Low Cost Range		High Cost Range
	Polymer, feed	X
	Filtration, system	X
	Filter media, mixed	X
X	Reverse osmosis*	X
	Clearwell, ground level	X
	Filter backwash	X
	Filter surface wash	X
X	Wastewater to sewer	X

* Includes cartridge filters, Na-hex feed, instrumentation, pumping, degasifier and system housing.



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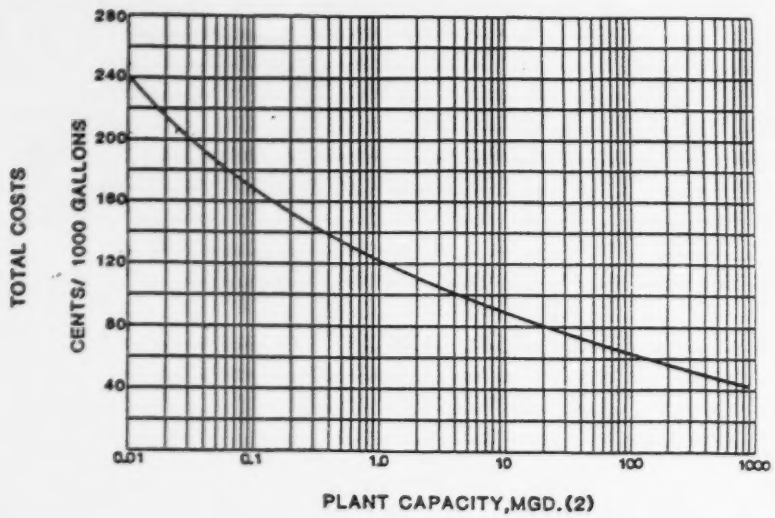


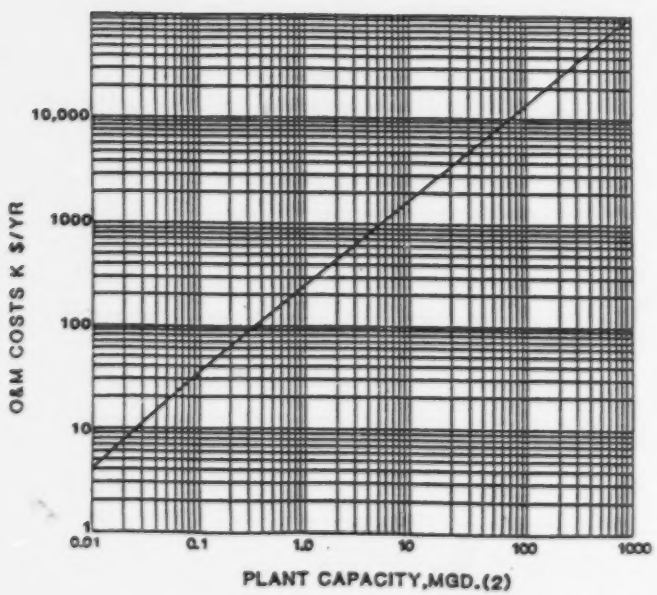


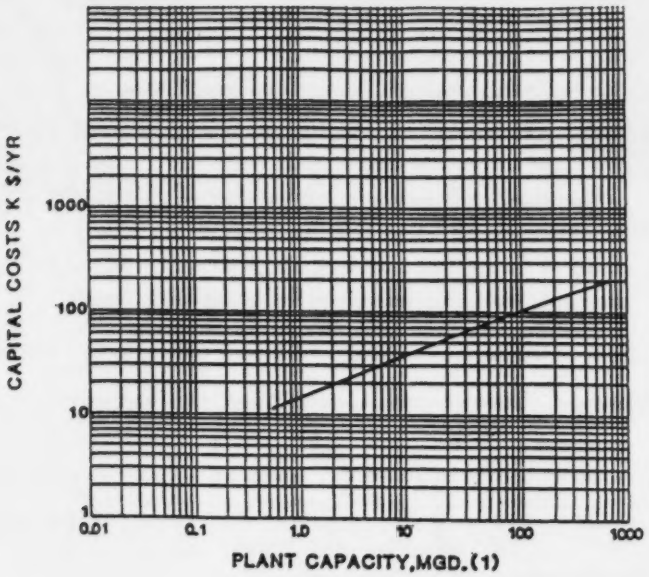
FIGURE 12

TREATMENT COSTS FOR FLUORIDE REMOVAL BY REVERSE OSMOSIS (50/50 BLEND)

3. Lime Softening, Modified: Preliminary cost estimates for the optimization of lime softening as an existing softening plant were developed based on the following assumptions:

- Lime, excess lime or lime-soda ash softening facilities exist.
- Lime feed system requires modification to feed larger quantity of lime.
- Lime feed in increased by 120 mg/L.
- Sufficient magnesium is present in the raw water for low range cost estimate. Magnesium chloride of 100 mg/L is added for high range cost estimates.
- Additional sludge disposal costs are included.

Cost estimates for modification of lime softening for fluoride removal are presented in Figure 13. The costs are dependent primarily on quantity of magnesium in the water source and pH selected for treatment. Additional chemicals are required to provide conditions for improved fluoride removal. The low range costs represent a lime softening plant modified to increase the lime dosage to operate at a higher pH. The high range costs include the same treatment with the additional costs for increasing magnesium content of the source water. The cost estimates for various plant capacities shown in Figure 13 are average costs of the low and high range systems.



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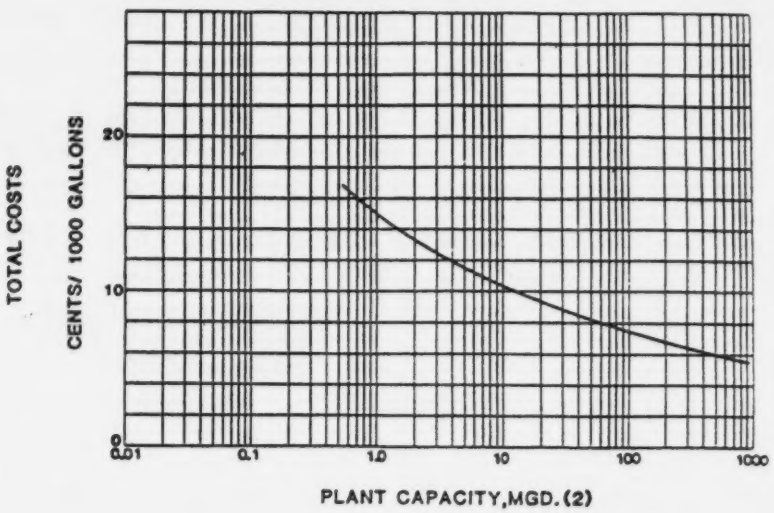


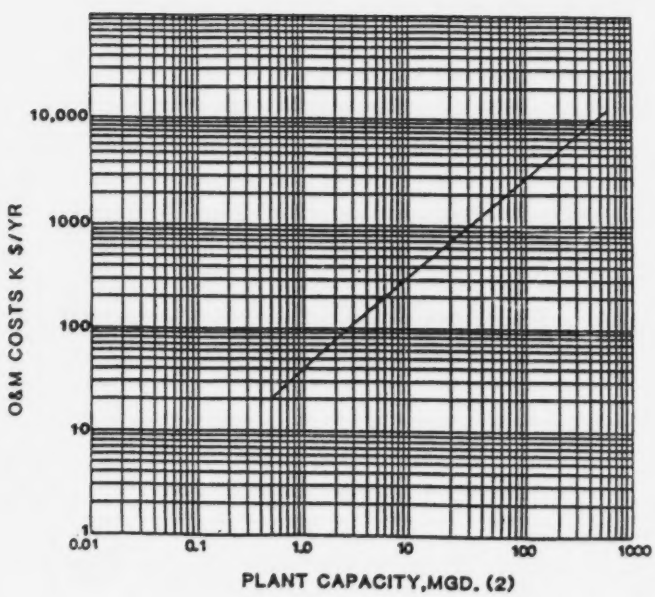


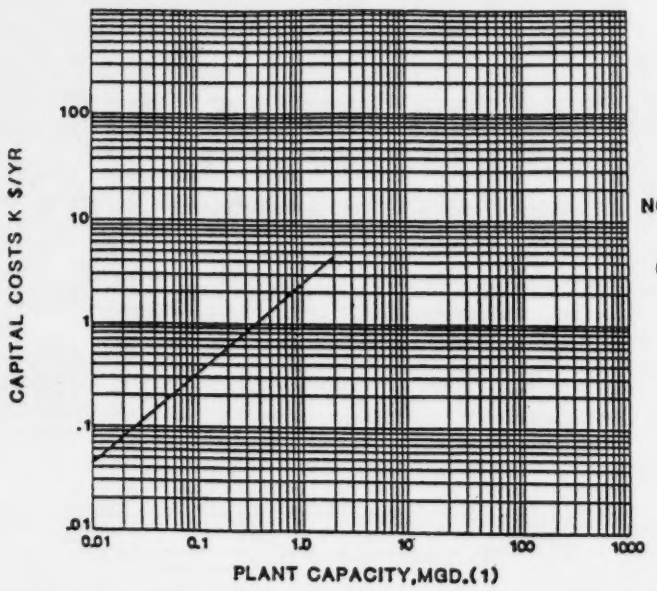
FIGURE 13

TREATMENT COSTS FOR FLUORIDE REMOVAL BY LIME SOFTENING, MODIFIED

4. Bottled Water: Cost estimates for bottled water were developed based on the following assumptions:

- The quality of the bottled water meets the MCL requirements for drinking water.
- The bottled water will be used for drinking and cooking only.
- Bottled water demand for drinking and cooking is based on 2 gallons per household per day with 2 deliveries per week per residence.
- The source of uncontaminated water is 12.5 miles from the community where the bottled water is required.
- Bottled water is delivered directly to the customers' door.
- Using higher fluoride water for household activities, other than cooking and drinking, presents no health danger.
- The costs of procuring water for bottling or its pretreatment are not included since these represent only a small fraction of the cost of bottling and delivery.
- Profits and overhead charges are not included since the water utility is responsible for the bottled water service.
- The route distance for each size system is based upon an estimate of the existing water main distribution length.

a. Bottled Water Delivered to 30 Percent of the Households: From the 1980 U.S. Census, it was determined that 30.4 percent of the families have children under 9 years old.[24] This is the age group considered most likely to be affected if the water consumed exceeds the fluoride MCL requirement. Using above assumptions the costs for bottled water for the smaller communities where 30 percent of the households receive bottled water are presented in Figure 14. Based on responses to a survey of bottled water distributors,[25] average values were used to develop capital and O&M costs for the different size systems.



NOTE:

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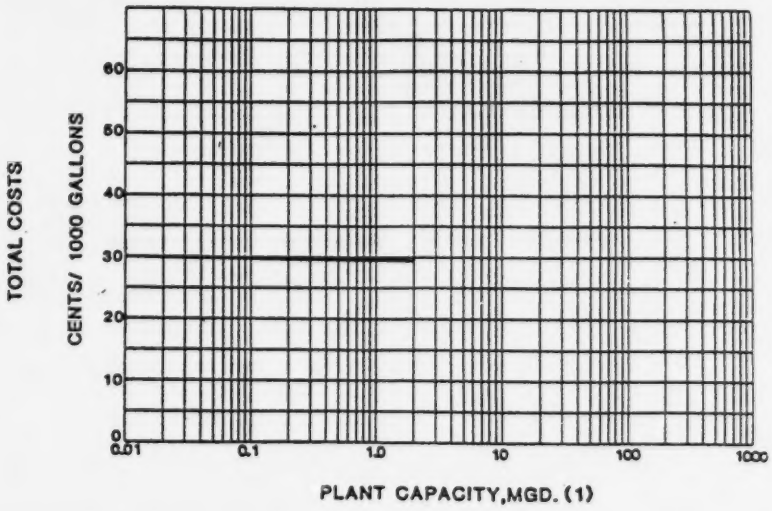


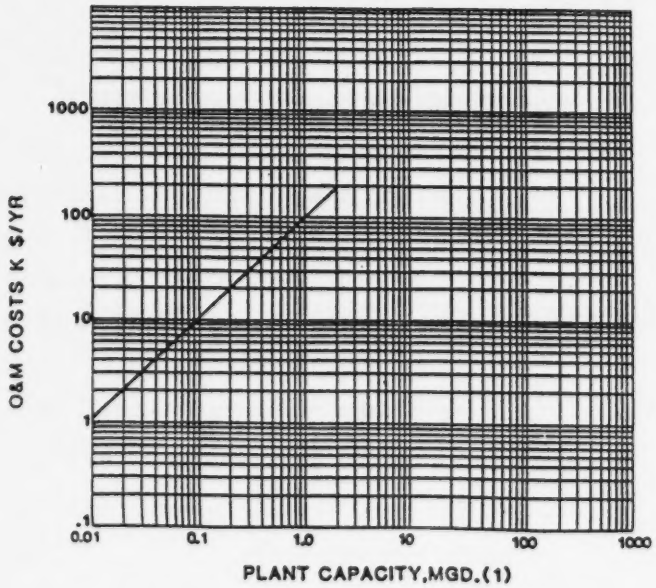
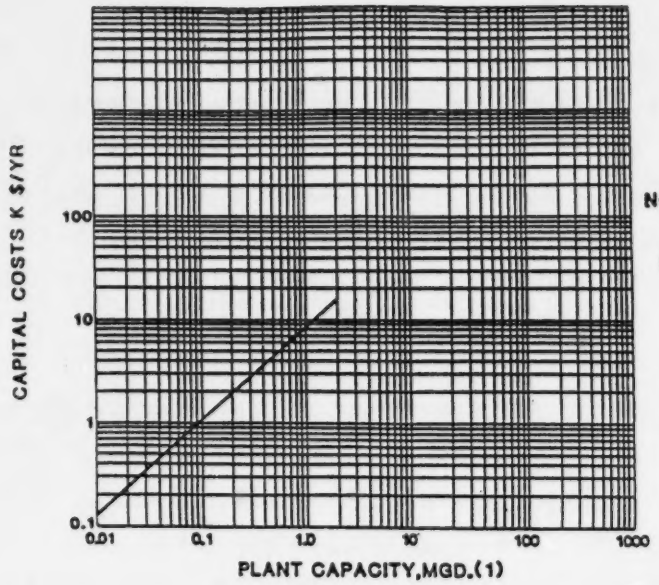


FIGURE 14

COSTS OF BOTTLED WATER
(30% OF THE HOUSEHOLDS)
FOR COMPLIANCE WITH THE FLUORIDE MCL

The total cost of bottled water was then prorated among all subscribers, which, when added to the cost of water provided by the utility, resulted in a cost per 1,000 gallons that is charged to all consumers. In this analysis all the water consumers in a community share the cost of bottled water, not just those who receive deliveries.

b. Bottled Water Delivered to 100 Percent of the Households: The cost of bottled water is substantially increased if 100 percent of the households are provided with bottled water. The cost estimates based on the above assumptions are directly proportioned to the number of households receiving the water, although some O&M economics of scale would result. Average costs are calculated the same as for delivery to 30 percent of the households. The cost estimates are presented in Figure 15 where 100 percent of the households receive bottled water.



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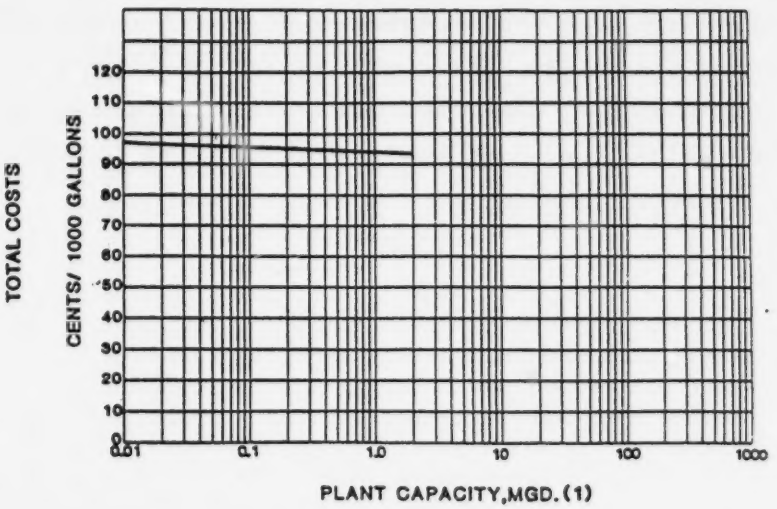


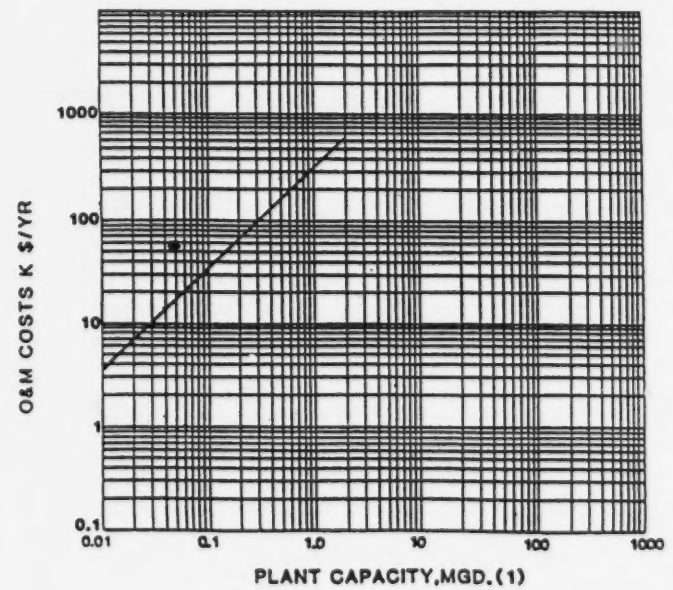


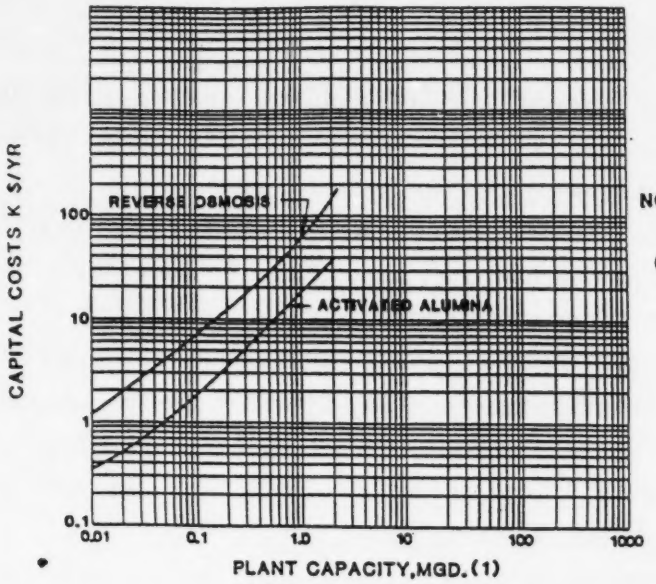
FIGURE 15

COSTS OF BOTTLED WATER
(100% OF THE HOUSEHOLDS)
FOR COMPLIANCE WITH THE FLUORIDE MCL

5. Point-of-Use: For the purpose of developing preliminary cost estimates for activated alumina and reverse osmosis point-of-use treatment, the following assumptions were utilized:

- The water utility or community has responsibility for the purchase of the point-of-use device, its installation and regularly scheduled maintenance.
- A single type of device will be selected for all residences so as to insure compliance with the MCL requirement, and all customers will receive equal and uniform maintenance consisting of one replacement per year of the treatment cartridge.
- Filters and screening units are not included as a pretreatment protection for the point-of-use device, but may be necessary where feed water quality requires filtration.
- No costs for monitoring water quality have been included but if required, would increase O&M costs appreciably.
- Point-of-use capacity is based on one unit per household for use in cooking and drinking only. Unit capacity is estimated at not less than two gpd per household use.
- The total number of units required for each system is determined on the basis that each household will be supplied with 300 gpd by the utility.

a. Point-of-Use 30 Percent of the Households: Preliminary cost estimates were prepared using the above assumptions for activated alumina and reverse osmosis point-of-use treatment. Costs for activated alumina and reverse osmosis devices installed in 30 percent of the households corresponding to the water production plant capacities for the various size communities are shown in Figure 16. The costs for point-of-use treatment for the smaller communities where 30 percent of the households have point-of-use devices installed are presented in Figure 16. The input parameters used to develop capital and operating costs for point-of-use treatment are presented in Appendix C. The total



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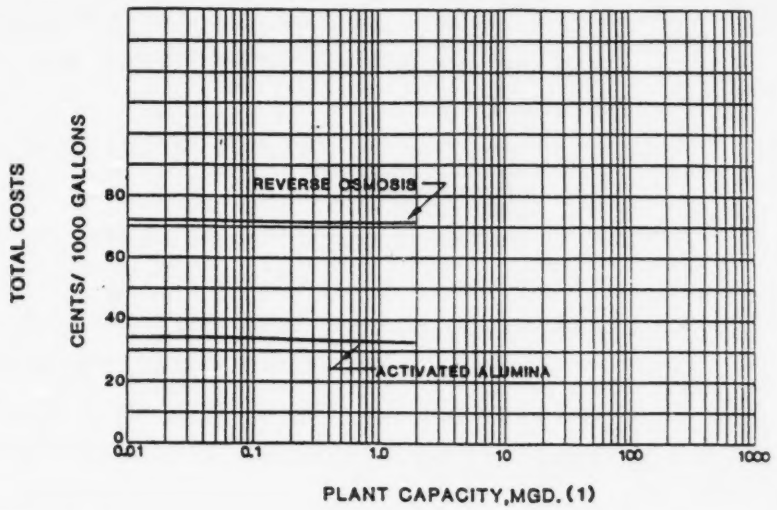


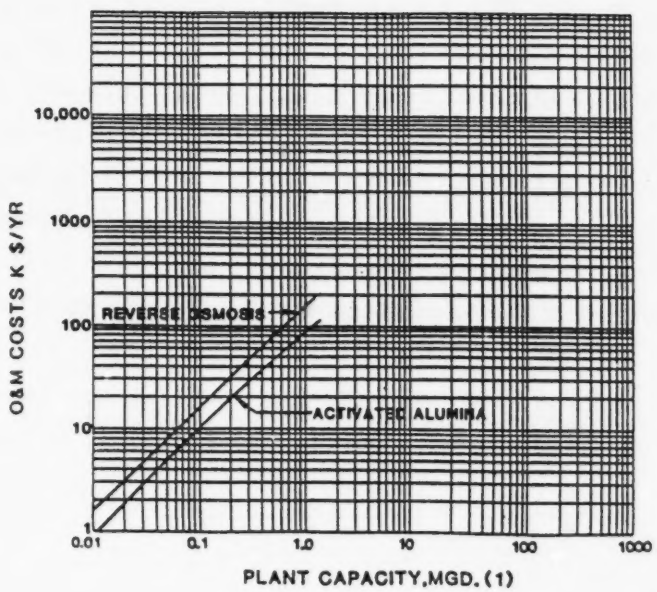
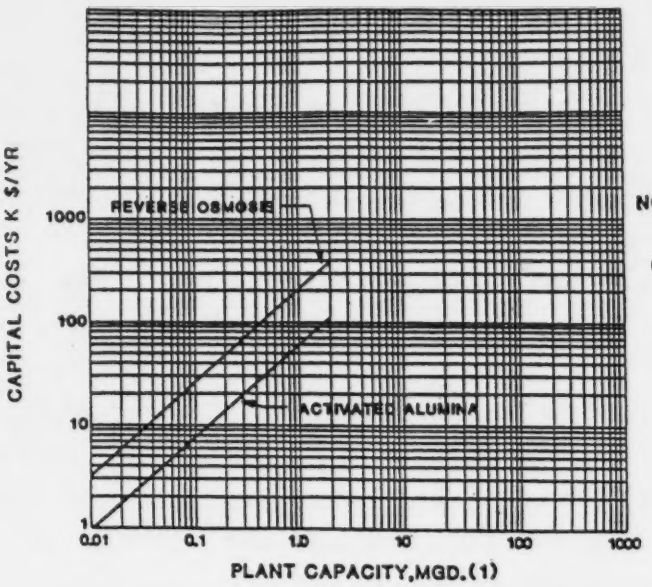


FIGURE 16

TREATMENT COSTS FOR FLUORIDE REMOVAL BY POINT-OF-USE (30% OF THE HOUSEHOLDS)

cost of point-of-use treatment was then prorated among all subscribers, which, when added to the cost of water provided by the utility, resulted in a cost per 1,000 gallons that is charged to all consumers. In this analysis all the water consumers in a community share the cost of point-of-use treatment, not just those who have the device installed.

b. Point-of-Use, 100 Percent of the Households: Cost estimates for point-of-use treatment, for activated alumina and reverse osmosis devices covering 100 percent of the households, are shown in Figure 17. The costs are directly proportional to the number of families or households where point-of-use devices are installed. Except for the number of households served, the assumptions and criteria for determining costs are the same as for the 30 percent of the households.



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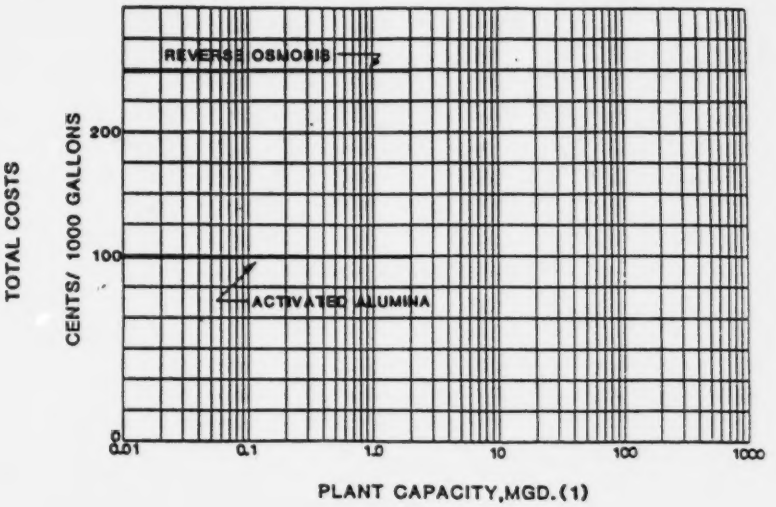


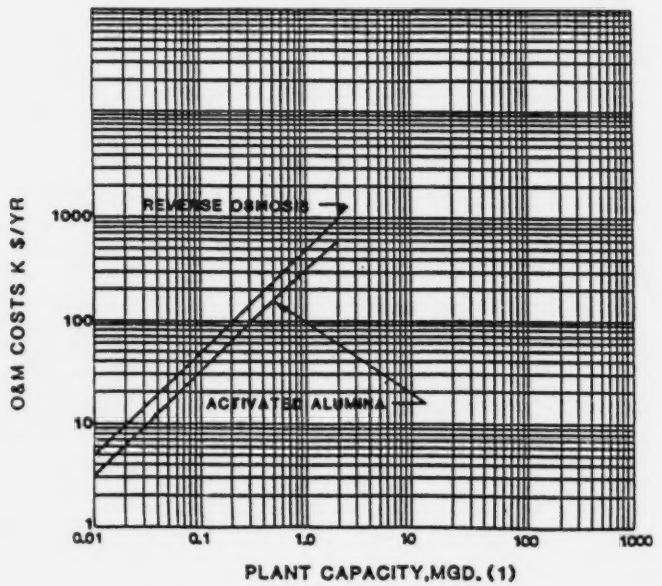


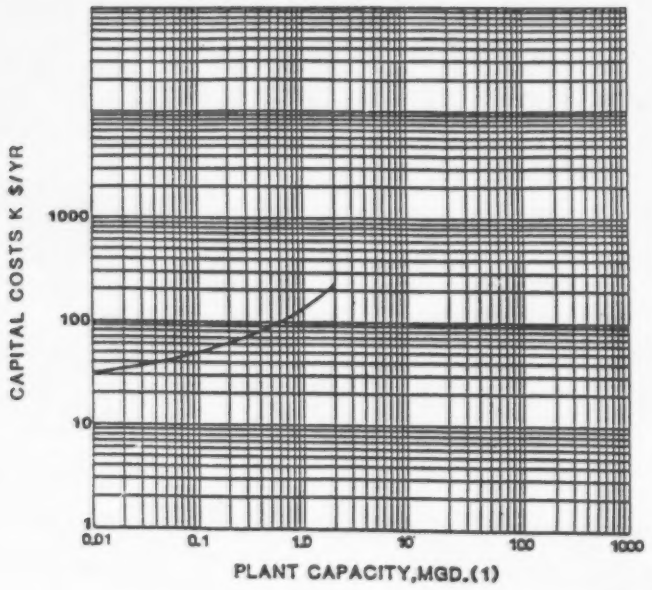
FIGURE 17

TREATMENT COSTS FOR FLUORIDE REMOVAL BY POINT-OF-USE (100% OF THE HOUSEHOLDS)

6. Regionalization: For the purpose of developing preliminary regionalization cost estimates, the following assumptions were utilized:

- A host community having an adequate supply of water meeting the MCL requirements exists within a reasonable distance.
- Costs for new facilities are for the pumping stations and transmission pipelines connecting the two communities.
- The community with the water quality problem is paying a certain amount for procurement and treatment of its existing water supply and it is assumed that the neighboring community costs for procurement and treatment of water will be the same. The cost of procurement and treatment of water is influenced by the size of the system, quality of source water, local politics and relations between the two communities and are so variable that analyses of these costs are not practical for this document.
- Expected life of the pumping station and transmission pipeline are: 30 and 50 years respectively; static head of 33 feet/mile of pipeline, Hazen-Williams coefficient equal to 100.
- The regionalization option will only be applicable in communities where an assumption of laying transmission mains in undeveloped areas may be valid (cost of transmission mains may vary widely depending upon the state of development of the area).
- An adequate water distribution system exists within the community with the water quality problem.

Cost estimates for the regionalization method for obtaining water meeting the MCL requirements are presented in Figure 18. The low costs represent a pipeline length of 3.0 miles, while the average and high costs were developed using a pipeline length of 7.5 and 10.5 miles respectively. In actuality, the pipeline



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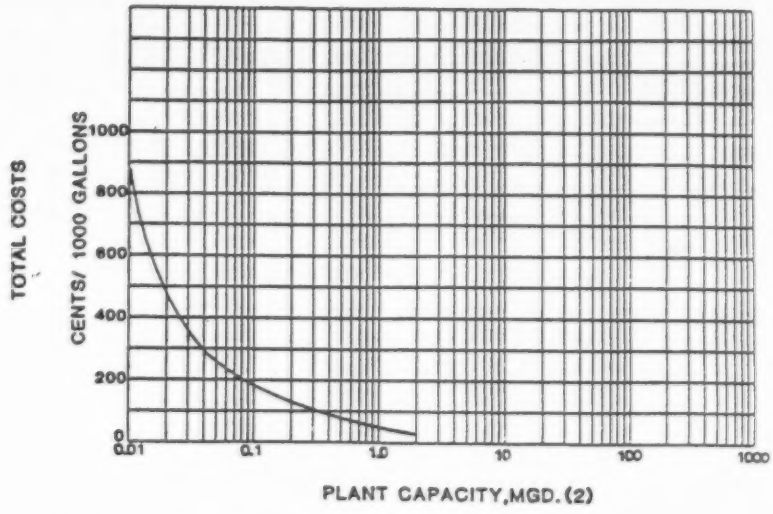


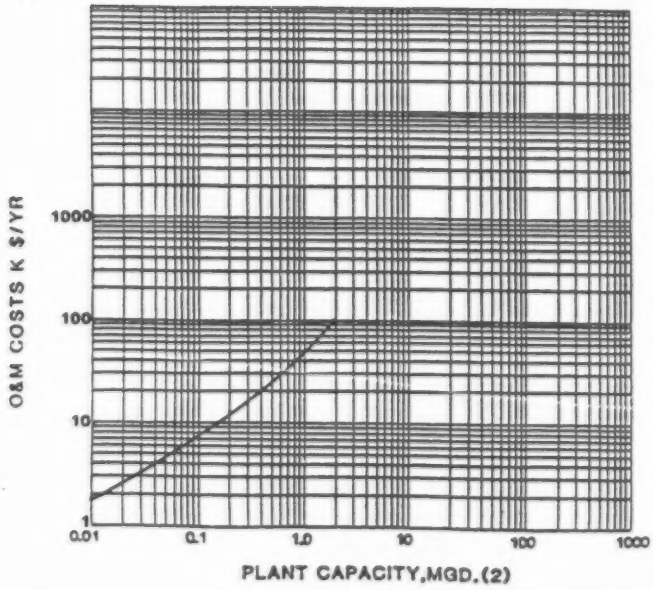


FIGURE 18

COSTS OF REGIONALIZATION FOR COMPLIANCE WITH MCL

length required for interconnection of large communities would be greater as the size of the community increased. The limiting factor for the larger communities is not cost but the diminished probability of finding a suitable host community within a reasonable distance that has the ability to take on the additional water demand. For this reason, the regionalization alternative was not simulated for the larger systems. The assumption of "underdeveloped areas" makes the pipeline cost function inappropriate for these size categories.

7. Alternate Source: For the purpose of developing preliminary alternate source cost estimates, the following assumptions are utilized:

- Tapping a new source would require a raw water transmission main of between 5 and 10 miles, with an average of 7.5 miles.[25]
- Alternate water source does not exceed the MCL for fluoride.
- Costs associated with acquiring new land or easements for the transmission main are not included due to the site specific nature of these costs; however, these costs could be considerable.
- The existing treatment and distribution facilities would be used with the new source without major operating changes.
- For surface water sources:
  - Raw water intake facilities would be installed.
  - Raw water low-lift pumping at a total dynamic head of 50 feet (average) would be required.
- For groundwater sources:
  - New wells at a maximum capacity of 1 mgd each would be installed.
  - The costs of a geologic study were not included because of the site specific nature of these studies; however, these costs could be considerable.

The specific unit processes that were applied to each system size are shown in Table 4. Costs were developed for each category based on different combinations of these unit processes. The range of costs provided the low and high costs for each category, and an average cost was determined by using the weighting factors shown in Table 5. The cost estimates for various plant capacities shown in Figure 19 are the weighted average costs.

TABLE 4
UNIT PROCESSES APPLIED TO SYSTEM SIZE CATEGORIES

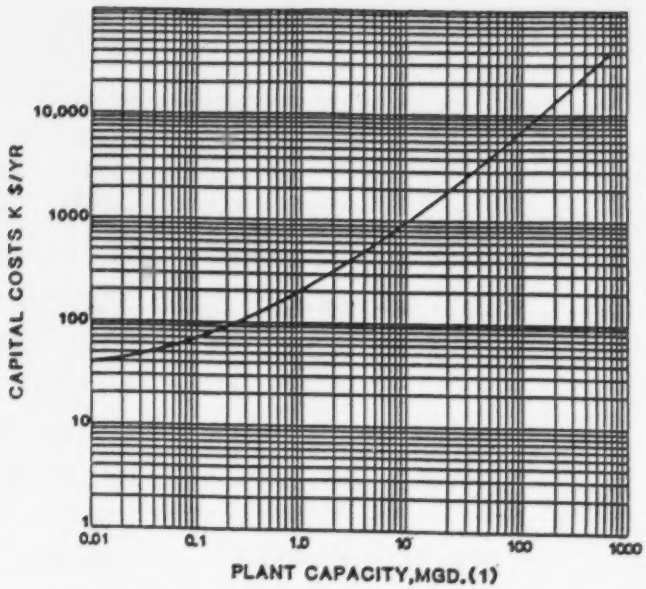
Unit Process	System Size, MGD								
	0.01	0.04	0.14	0.44	0.90	1.55	8.82	75.99	721.98
1. Wells	X	X	X	X	X	X	X	---	---
2. Well Pump, Turbine	X	X	X	X	X	X	X	---	---
3. Well Pump, Submersible	X	X	X	X	X	X	X	---	---
4. Transmission Pipeline	X	X	X	X	X	X	X	X	X
5. Pump Station	X	X	X	X	X	X	X	X	X
6. Impounded Reservoir	X-S	X-S	X-S	X-S	X-S	X-S	X-L	X-L	X-L
7. Intake Tower	---	---	---	---	---	---	X-L	X-L	X-L
8. Raw Water Pumping	X	X	X	X	X	X	E	E	E
9. Packaged Treatment Plant	X	X	X	X	X	X	---	---	---
10. Sludge Handling	X-S	X-S	X-S	X-S	X-S	X-S	X-L	X-L	X-L
11. Rapid Mix and Coagulation	---	---	---	---	X	X	E	E	E
12. Clarification	---	---	---	---	X	X	E	E	E
13. Gravity Filtration	---	---	---	---	X	X	E	E	E

New Facility: X
Existing Facility: E
Small Design: X-S
Large Design: X-L

TABLE 5
WEIGHTING FACTORS FOR ALTERNATE SOURCES

MGD	SOURCE (PERCENTAGE)		TREATMENT FOR SURFACE WATER (PERCENTAGE)			
	Ground-water*	Surface Water	Use Existing Filters	Package Plant	Need Filter Only	Use Existing Treatment
0.01	75	25	6.25	----	18.75	----
0.04	75	25	6.25	----	18.75	----
0.14	75	25	6.25	----	18.75	----
0.44	75	25	6.25	----	18.75	----
0.90	50	50	----	12.5	12.5	25
1.55	50	50	----	12.5	12.5	25
8.82	10	90	----	----	----	90
75.99	10	90	----	----	----	90
721.98	10	90	----	----	----	90

* No treatment required.



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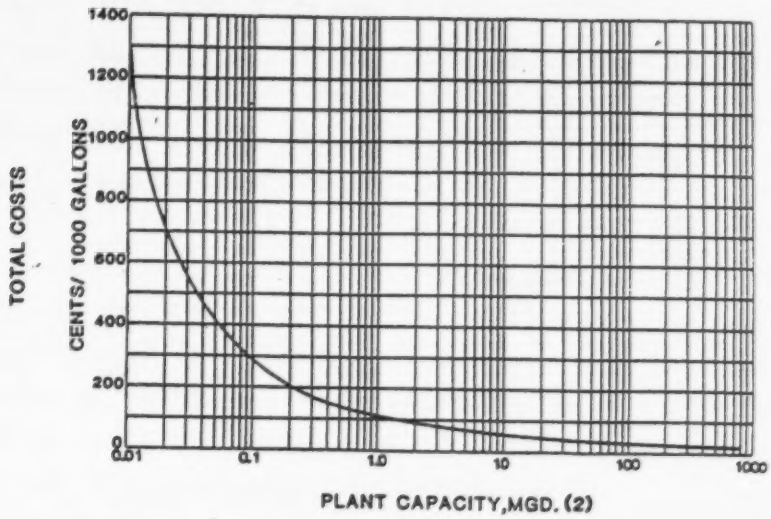
(2) WATER PRODUCTION CAPACITY OF THE PLANT USED IN O&M AND TOTAL COST ESTIMATES.



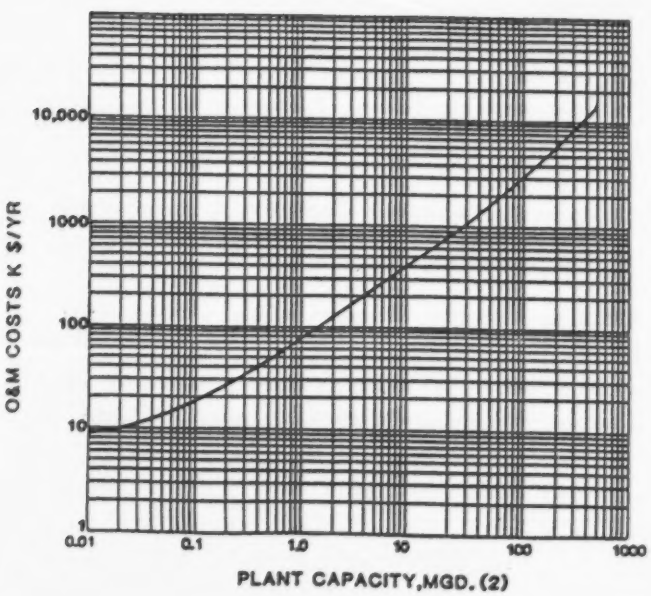


FIGURE 19

COSTS FOR COMPLIANCE WITH MCL BY DEVELOPMENT OF AN ALTERNATE WATER SOURCE

SUMMARY

A summary of the total costs for all the technologies is presented in Figure 20. Only a few technologies having total costs less than $1.00/1,000 gallons of water are available for the small water system. Capital and operating costs are presented in Tables 6 and 7. Amortizing the capital cost at 12 percent over 20 years and adding the operating costs give a comparison of the treatment methods based upon the cost in cents per 1,000 gallons of water treated. These costs are presented in Table 8.

The various treatment and compliance technologies for fluoride removal exhibit certain advantages and disadvantages, depending on the system size category and the level of fluoride removal which is necessary for a given water supply. Some of the potential advantages and disadvantages of utilizing a treatment technique at a central facility for removing fluoride are outlined below:

Advantages

- Control of the finished water quality is easier to maintain at a central treatment facility.
- Implementation and maintenance of a treatment technology may be easier, especially because of water quality monitoring, than implementation of point-of-use or bottled water techniques, depending on the system size.

Disadvantages

- The capital costs of a conventional central treatment technology may be prohibitive for many small water systems.
- The operation and maintenance of a central treatment technique may be beyond the capabilities of a small water system.
- Fluoride removal is provided for the entire population served whereas it may only be necessary for a portion of the population to receive defluoridated water.

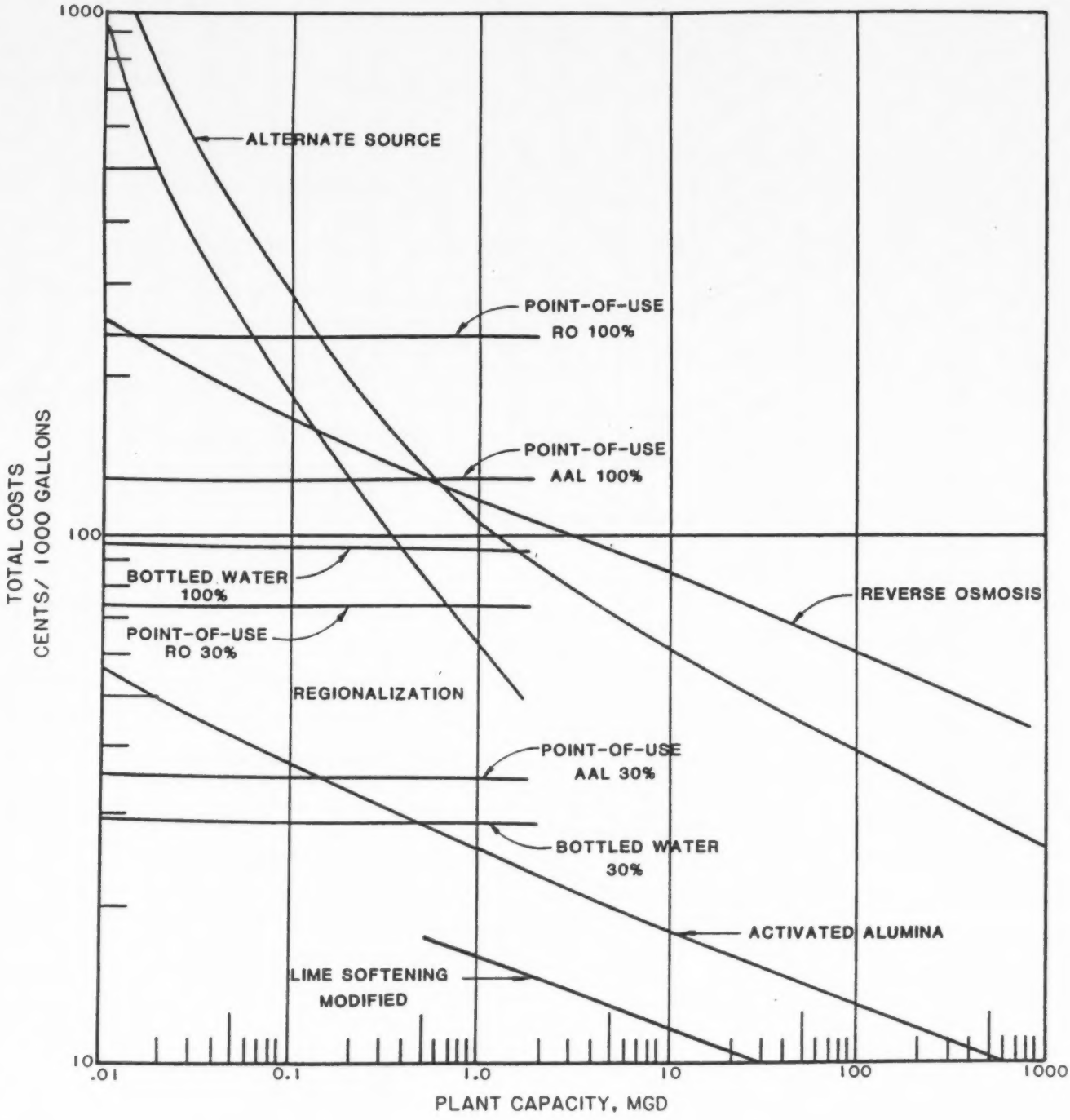


FIGURE 20 TOTAL COSTS OF THE TECHNOLOGIES
FOR COMPLIANCE WITH FLUORIDE MCL

TABLE 6

SUMMARY OF COSTS FOR COMPLIANCE WITH MCL

CAPITAL COSTS $K/YEAR

1982 COSTS	POP. SERVED	25-99	100-499	500-999	1,000-2,499	2,500-4,999	5,000-9,999	10,000-99,999	100,000-999,999	>1,000,000
TREATMENT METHODS	MGD	.01	.04	.14	.44	.90	1.55	8.82	76	722
	REM. EFF. %									
ACTIVATED ALUMINA	>90	0.96	2.66	6.66	15.43	26.07	38.83	139	673	3,507
REVERSE OSMOSIS	>90	3.22	10.06	28.14	72.08	129.73	202.73	845	4,956	31,484
LIME SOFTENING, MODIFIED	<65	-	-	-	-	13.11	16.23	32.15	74.94	181.53
BOTTLED WATER*	N/A	.04	.14	.43	1.18	2.23	3.60	-	-	-
BOTTLED WATER**	N/A	.13	.46	1.43	4.00	7.62	12.44	-	-	-
POINT-OF-USE, ACT. ALUMINA*	N/A	.32	.96	2.56	7.03	16.93	32.91	-	-	-
POINT-OF-USE, REVERSE OSMOSIS*	N/A	1.10	3.31	8.85	24.38	58.67	114.12	-	-	-
POINT-OF-USE, ACT. ALUMINA**	N/A	1.05	3.15	8.41	23.12	55.70	108.25	-	-	-
POINT-OF-USE, REVERSE OSMOSIS**	N/A	3.64	10.90	29.10	80.20	193.00	375.40	-	-	-
REGIONALIZATION	N/A	31.85	36.87	53.46	84.39	140.79	180.48	-	-	-
ALTERNATE SOURCE	N/A	40.11	48.00	72.36	121.69	212.18	283.75	1,223	6,060	39,107

* 30% of Households
** 100% of Households

TABLE 7

SUMMARY OF COSTS FOR COMPLIANCE WITH MCL

OPERATING COSTS $K/YEAR

1982 COSTS	POP. SERVED	25-99	100-499	500-999	1,000-2,499	2,500-4,999	5,000-9,999	10,000-99,999	100,000-999,999	>1,000,000
TREATMENT METHODS	MGD	.01	.03	.08	.22	.53	1.03	5.51	51	515
	REM. EFF. %									
ACTIVATED ALUMINA	>90	.92	2.44	5.86	14.44	31.63	57.20	255	1,846	14,613
REVERSE OSMOSIS	>90	4.54	11.73	27.38	65.60	140.23	248.97	1,060	7,204	53,447
LIME SOFTENING, MODIFIED	< 65	-	-	-	-	22.50	41.26	190	1,442	11,966
BOTTLED WATER*	N/A	.83	4.00	10.01	23.35	50.05	100.05	-	-	-
BOTTLED WATER**	N/A	3.42	10.15	26.84	73.14	174.83	337.76	-	-	-
POINT-OF-USE, ACT. ALUMINA*	N/A	.98	2.97	7.90	21.76	52.42	92.03	-	-	-
POINT-OF-USE, REVERSE OSMOSIS*	N/A	1.54	4.65	12.40	34.28	82.29	144.46	-	-	-
POINT-OF-USE, ACT. ALUMINA**	N/A	3.22	9.76	25.97	71.58	172.45	302.72	-	-	-
POINT-OF-USE, REVERSE OSMOSIS**	N/A	5.06	15.30	40.78	112.78	270.70	475.20	-	-	-
REGIONALIZATION	N/A	1.70	2.70	6.08	14.18	26.97	51.24	-	-	-
ALTERNATE SOURCE	N/A	9.35	11.21	17.91	34.15	52.78	87.14	269	1,756	15,933

* 30% of Households
** 100% of Households

TABLE 8

SUMMARY OF COSTS FOR COMPLIANCE WITH MCL

COSTS IN CENTS/1000 GALLONS

1982 COSTS	POP. SERVED	25-99	100-499	500-999	1,000-2,499	2,500-4,999	5,000-9,999	10,000-99,999	100,000-999,999	>1,000,000
TREATMENT METHODS	MGD	.01	.03	.08	.22	.53	1.03	5.51	51	515
	REM. EFF. %									
ACTIVATED ALUMINA	> 90	56	47	40	34	30	27	20	14	10
REVERSE OSMOSIS	> 90	243	206	178	152	133	121	94	67	47
LIME SOFTENING, MODIFIED	< 65	-	-	-	-	17	15	12	8	6
BOTTLED WATER*	N/A	30	30	30	30	29	29	-	-	-
BOTTLED WATER**	N/A	97	97	96	95	94	94	-	-	-
POINT-OF-USE, ACT. ALUMINA*	N/A	36	36	36	36	36	36	-	-	-
POINT-OF-USE, REVERSE OSMOSIS*	N/A	73	73	73	73	73	73	-	-	-
POINT-OF-USE, ACT. ALUMINA**	N/A	118	118	118	118	118	118	-	-	-
POINT-OF-USE, REVERSE OSMOSIS**	N/A	239	239	239	239	239	239	-	-	-
REGIONALIZATION	N/A	919	361	204	123	87	62	-	-	-
ALTERNATE SOURCE	N/A	1,355	541	309	194	137	99	75	43	29

* 30% of Households

** 100% of Households

Some potential advantages and disadvantages of the various potential compliance techniques or point-of-use technologies are outlined below:

Advantages

- For some technologies, only that portion of the water supplied which is used for consumption is treated.
- May represent the most cost-effective solution for the very small water systems.
- May be easier to operate and maintain for the very small systems.

Disadvantages

- Control of the finished water fluoride level may be difficult for some of the techniques.
- For point-of-use techniques, it would be necessary to maintain a number of treatment units compared to maintaining one central treatment unit, with commensurate increase of monitoring burden.

REFERENCES

1. Interim Primary Drinking Water Regulations; Amendments. U.S. Environmental Protection Agency. Federal Register 45(168):57332-57, 1980.
2. Defluoridation Study for the Arizona Department of Health Services. Planning Research Company (PRC), Toups Corp., 1979.
3. Rubel, F., Jr. and Woosley, R.D., The removal of excess fluoride from drinking water by activated alumina. Journal AWWA 71(1):45-49, 1979.
4. Rubel, F., Jr. and Woosley, R.D., Removal of Excess Fluoride from Drinking Water. U.S. Environmental Protection Agency, Office of Water Supply, 1978.
5. Maier, F.J., Partial defluoridation of water. Public Works 91:11-14, 1960.
6. Community Water Supply Study. Analysis of National Survey Findings. U.S. Department of Health, Education, and Welfare, Public Health Service, Bureau of Water Hygiene, 1970.
7. Sorg, T.J., Treatment technology to meet the interim primary drinking water regulations for inorganics. Journal AWWA 70(2):105-12, 1978.
8. Singh, G. and Clifford, D.A., The Equilibrium Fluoride Capacity of Activated Alumina. U.S. Environmental Protection Agency, EPA-600/S2-81-082, 1981.
9. EPA/NSF Study of Defluoridation of Drinking Water in Small Communities and Point-of-Use Reduction of Volatile Halogenated Organic Contaminants from Drinking Water. U.S. Environmental Protection Agency, Ninth Quarterly Report, 1983.
10. Desalting Plants Inventory Report No. 6. U.S. Department of the Interior, 1977.
11. Kosarek, L.J., Purifying water by reverse omsosis, part I. Plant Engineering 33(16):103, 1979.

12. Huxstep, M.R., Inorganic Contaminant Removal from Drinking Water by Reverse Osmosis. U.S. Environmental Protection Agency, 1981.

13. Hindin, E., Dunstan, G.H., et al., Water Reclamation by Reverse Osmosis. Bulletin 310, Technical Extension Service. Washington State University, 1968.

14. Mattson, M.E. and Lew, M., Recent advances in reverse osmosis and electrodialysis membrane desalting technology. Desalination 41:1-24, 1982.

15. Desalting Seawater and Brackish Water: Cost Update 1979. Oak Ridge National Laboratories, ORNL/TM-6912, 1979.

16. Parametric Study on Brackish Water Membrane Desalting Plants. Volume I. U.S. Department of the Interior, 1979.

17. Savinelli, E.A. and Black, A.P., Defluoridation of water with activated alumina. Journal AWWA 50(1):33-44, 1958.

18. Scott, R.D., Kimberly, A.E., et al., Fluoride in Ohio water supplies. Journal AWWA 29(1):9-25, 1937.

19. Culp, R.L. and Stoltenberg, H.A., Fluoride reduction at LaCrosse, Kansas. Journal AWWA 50(3):423-31, 1958.

20. Goodwin, R.C. and Litton, J.B., Removal of fluorides from public water supplies. Industrial and Engineering Chemistry 33(8):1046-48, 1941.

21. Bottled water: part 103 - quality standards for foods with no identity standards; part 120 - Processing and bottling of bottled drinking water. Food and Drug Administration/HEW. Federal Register 44(45):12169-75, 1979.

22. Bauman, D.D. and Dworkin, D.M., Consumer Perception and Choice of Drinking Water Quality. In: Safe Drinking Water: Current and Future Problems, Resources for the Future, Russell, C.S., Ed. Resources for the Future, 1978.

23. Drinking Water and Health. Volumes I and II. U.S. National Academy of Sciences, 1977.

24. Percentage of Families with Children Beneath a Certain Age: Fluoride and Nitrate. Memorandum. U.S. Environmental Protection Agency, 1982.

25. Deb, A.K., et al., Alternative Technologies for Small Water System Management. Supported by National Science Foundation, Grant No.: 1 SP 80-15075. R. F. Weston, Inc., 1982.
26. Results of Monitoring of Arsenic Removal Equipment in Hudson, New Hampshire. U.S. Environmental Protection Agency, Region I, Drinking Water Branch, 1982.
27. Personal communication, R. Lake, 1982.
28. Adler, H., Klein, G., et al., Removal of fluorides from potable water by tricalcium phosphate. Industrial and Engineering Chemistry 30(2):163-65, 1938.
29. Thompson, J. and McGarvey, F.X., Ion-exchange treatment of water supplies. Journal AWWA 45(2):145-52, 1953.
30. Data Collection and Analysis of Commercial Membrane Desalination Plants. Volumes I, II and III. U.S. Department of the Interior, 1980.
31. Katz, W.E., Design of Medium-to-Large Electrodialytic Water Demineralizers. Advances in Chemistry Series No. 38: Saline Water Conversion II. American Chemical Society, 1963.
32. Clark, R.M. and Dorsey, P., A model of costs for treating drinking water. Journal AWWA 74(12):618-27, 1982.
33. Gumerman, R.C., Culp, R.L., et al., Estimating Water Treatment Costs. Volume 1: Summary. U.S. Environmental Protection Agency, EPA-600/2-79-162a, 1979.
34. Gumerman, R.C., Culp, R.L., et al., Estimating Water Treatment Costs. Volume 2: Cost Curves Applicable to 1 to 200 mgd Treatment Plants. U.S. Environmental Protection Agency, EPA-600/2-79-162b, 1979.
35. Hansen, S.P., Gumerman, R.C., et al., Estimating Water Treatment Costs: Volume 3; Cost Curves Applicable to 2,500 gpd to 1 mgd Treatment Plants. U.S. Environmental Protection Agency, EPA-600/2-79-162c, 1979.
36. Market trends. Engineering News-Record 208(9):50, 1982.

TABLE A-1

EFFICIENCIES OF FLUORIDE REMOVAL TECHNOLOGIES

TABLE A-1
EFFICIENCIES OF FLUORIDE REMOVAL TECHNOLOGIES

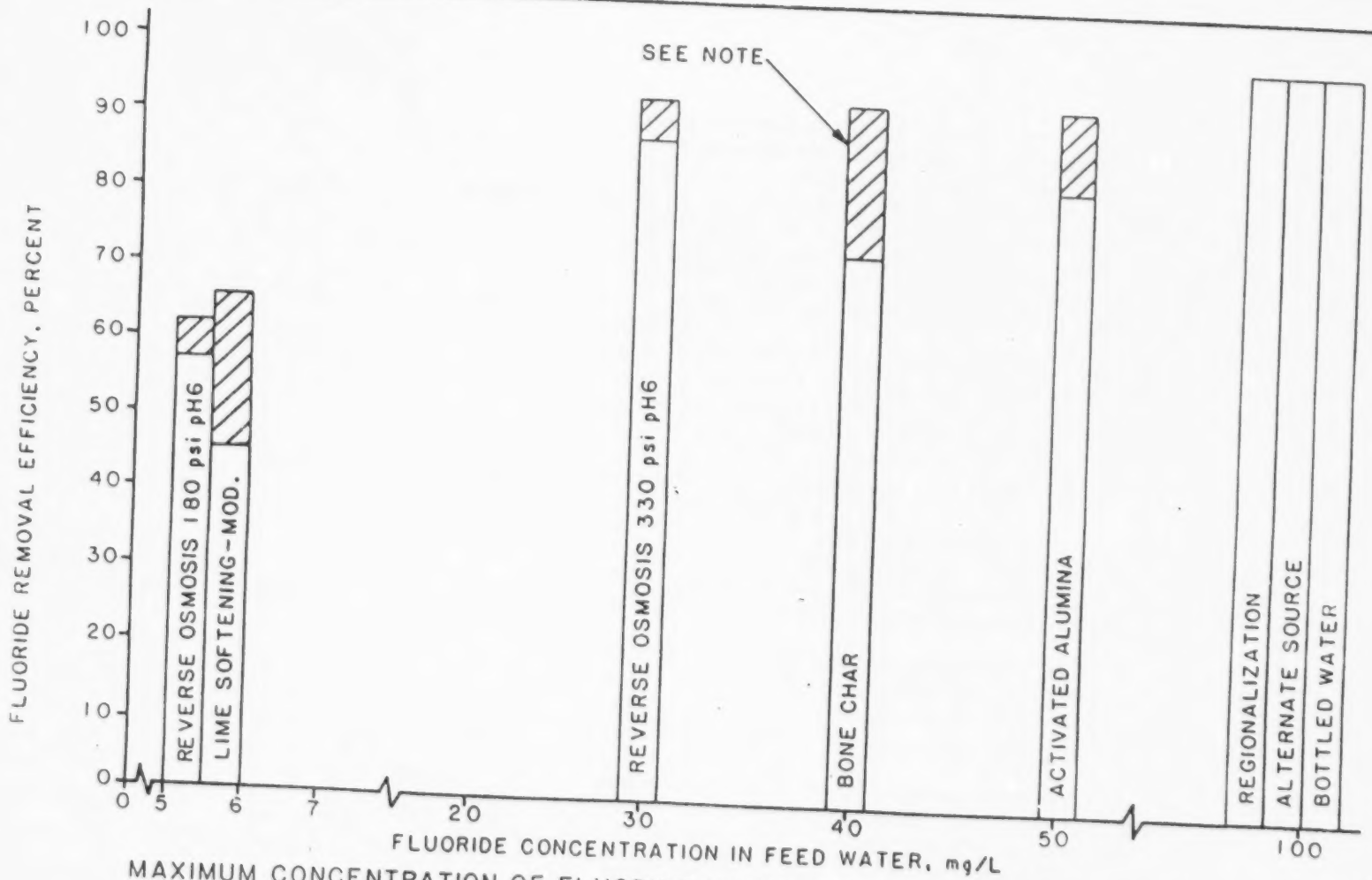
TREATMENT	INFLUENT F^- CONCENTRATION mg/L	FLUORIDE REMOVAL PERCENTAGE	COMMENTS	REFERENCE
Activated Alumina	8.0	<87	Bartlett, TX, 0.5 mgd plant, 500 cuft of AA. Capacity of AA decreased from 700 to 400 grF$^-$/cuft when influent fluoride went from 8.0 to 3.0. Effluent water maintained at 1.0 mg/L F^-; pH of raw water varied.	1,2,3,4,5
	7.5	>95	Lake Tamerisk, Desert Center, CA, 1.5 mgd plant adjusts pH from 7.9 to 5.5 with sulfuric acid; blending treated water.	1,5,6,7
	4.5	>95	Rencon Water Co., Vail, AZ, 0.7 mgd plant reduces raw water pH from 7.5 to 5.5; uses granular AA, mesh size 28 to 48; blending treated water.	1,5,6,7
	6.0	>95	Gila Bend, AZ, 0.75 mgd plant, raw water pH reduced from 8.3 to 5.5; uses granular AA; blending treated water.	6,7,8
	4.3	>99	Pilot-plant tests at Mt. Pleasant, SC, using 10,000 gal of water, 0.88 cuft of AA neutralized with muriatic acid. Influent raw water pH 5.5.	4
	2.2	>99	Pilot-plant tests at Conway, SC, capacity 8500 gal. Conditions same as Mt. Pleasant, SC, study.	4
	2.31	93-98	Waterville Valley, NH, study using fluidized AA at flow rates 6.6 to 20.2 gpm/sqft; pH 6.8. Alkalinity was also removed causing pH to drop from 4.3 to 4.0.	9

TABLE A-1
EFFICIENCIES OF FLUORIDE REMOVAL TECHNOLOGIES (Continued)

TREATMENT	INFLUENT F^- CONCENTRATION mg/L	FLUORIDE REMOVAL PERCENTAGE	COMMENTS	REFERENCE
Lime Softening	2.2	45	Bloomdale, OH, 0.1 mgd plant adds lime to reduce fluoride but does not soften water. Mg reduced from 98 to 52 mg/L.	10
	1.5	53	Alger, Hardin County, OH, 0.14 mgd plant, reduces magnesium from 46 to 14 mg/L; treatment raises pH from 7.8 to 10.4. Effluent F^- concentration 0.7 mg/L.	11
	2.1	52	Baltimore, Fairfield County, OH, 0.44 mgd, raw Mg 23 mg/L, requires addition of 36 mg/L Mg to reduce F^- level to 1.0 mg/L. Resulting pH increases from 7.7 to 10.0.	11
	1.7	44	Mt. Sterling, Madison County, OH, 0.44 mgd Mg concentration 43.1 mg/L which reduces to 16 mg/L with the addition of lime. F^- is reduced to 0.95; pH raised 7.1 to 10.1.	11
	3.2	65	LaCrosse, KS, experiment added magnesium oxide or magnesium sulfate to improve fluoride removal.	12
Reverse Osmosis	58.5	98	Laboratory tests using a 7 cm RO cell with cellulose acetate membrane.	5, 13
	110.0	40-96	Experimental studies show fluoride removal is pH dependent. F^- removal ranges from 40 to 96% as pH increases from 5.5 to 7 using hollow fiber RO membranes.	5, 13
	4.7	93 high psig 60 low psig	Pilot-plant tests at Charlotte Harbor, FL, spiked raw water with various levels of F^-. Both high and low pressure systems operated simultaneously to produce 0.06 mgd. The high pressure system operated at 330 psig and the low at 180 psig. Influent water pH 6.	14
	7.1	91 high psig 58 low psig		
	8.8	90 high psig 58 low psig		
	12.6	92 high psig 62 low psig		

TABLE A-1
EFFICIENCIES OF FLUORIDE REMOVAL TECHNOLOGIES (Continued)

TREATMENT	INFLUENT F^- CONCENTRATION mg/L	FLUORIDE REMOVAL PERCENTAGE	COMMENTS	REFERENCE
Bone Char	9-12	91-95	Ft. Irwin, CA, 0.094 mgd plant, used bone char regenerated with caustic soda and phosphoric acid. Regenerate chemical costs were high; media loss of 2 to 4 inches annually; also decreased cycle times.	1,4
	6.7	75	Britton, SD, using 300 cuft bed of 28 to 48 mesh bone char. Regeneration every 450,000 gal. Lowered pH optimized the exchange capacity, so pH was maintained at 7.1.	1,4,5
Tricalcium Phosphate (Synthetic Bone Char)	30.0	99	Laboratory tests showed neither influent F^- concentration nor raw water pH have any significant effect (twice the capacity of AA). Excessive losses in media, 2.5 to 3.0% per regeneration.	4
	10.0	99	Laboratory tests neutralizing with carbon dioxide instead of hydrochloric acid. After 130 cycles no losses in media or fluoride removal capacity. F^- concentration reduced from 10 to 0.1 after 2377 BV; raw water pH 7.8 to 8.1; alkalinity 110 to 115 mg/L.	4
	5.2	92	Pilot-plant experiment with 1.3 cuft bed, 1.5 gpm, and 50 runs showed 1 lb/cuft caustic required for regeneration; media replacement of 5% every 300 cycles.	4
	2-14	70-96	Climax, CO, 0.3 mgd plant, installed 4 tanks each with 45 inches of media. One or 2 units regenerated each day with sodium hydroxide and carbonic acid.	4, 15



MAXIMUM CONCENTRATION OF FLUORIDE WHICH CAN BE REDUCED TO 2.0 mg/L WHEN THE MAXIMUM REMOVAL EFFICIENCY IS APPLIED.

NOTE: CROSS HATCH REPRESENTS RANGE OF REMOVAL EFFICIENCY.

FIGURE A-1

RANGE IN EFFICIENCY OF TREATMENT OR OPTIONS AVAILABLE FOR FLUORIDE REMOVAL

REFERENCES TO APPENDIX A

1. Defluoridation Study for the Arizona Department of Health Services. Planning Research Company (PRC), Toups Corp., 1979.
2. Savinelli, E.A. and Black, A.P., Defluoridation of water with activated alumina. Journal AWWA 50(1):33-44, 1958.
3. Maier, F.J., Partial defluoridation of water. Public Works 91:11-14, 1960.
4. Fluoride Reduction in Community Water Supplies. State of South Carolina, Department of Health and Environmental Control, 1980.
5. Sorg, T.J., Treatment technology to meet the interim primary drinking water regulations for inorganics. Journal AWWA 70(2):105-12, 1978.
6. Rubel, F., Jr. and Woosley, R.D., The removal of excess fluoride from drinking water by activated alumina. Journal AWWA 71(1):45-49, 1979.
7. Rubel, F., Jr. and Woosley, R.D., Removal of Excess Fluoride from Drinking Water. U.S. Environmental Protection Agency, Office of Water Supply, 1978.
8. Singh, G. and Clifford, D.A., The Equilibrium Fluoride Capacity of Activated Alumina. U.S. Environmental Protection Agency, EPA-600/S2-81-082, 1981.
9. Bishop, P.L. and Sansoucy, G., Fluoride removal from drinking water by fluidized activated alumina. Journal AWWA 70(10):554-59, 1978.
10. Finkbeiner, C.S., Fluoride reduction plant installed at village of Bloomdale, Ohio. Water Works Engineering 91(15):990,993, 1938.
11. Scott, R.D., Fluoride in Ohio water supplies. Journal AWWA 29(1):9-25, 1937.
12. Culp, R.L. and Stoltenberg, H.A., Fluoride reduction at LaCrosse, Kansas. Journal AWWA 50(3):423-31, 1958.
13. Hindin, E., Dunstan, G.H., et al., Water Reclamation by Reverse Osmosis. Bulletin 310, Technical Extension Service, Washington State University, 1968.

14. Huxstep, M.R., Inorganic Contaminant Removal from Drinking Water by Reverse Osmosis. U.S. Environmental Protection Agency, 1981.

15. Wamsley, R. and Jones, W.E., Fluoride removal. Water and Sewer Works 94(8):272, 1947.

APPENDIX B
ANALYTICAL METHODS FOR
FLUORIDE DETERMINATIONS IN POTABLE WATER

APPENDIX B

ANALYTICAL METHODS FOR FLUORIDE DETERMINATIONS IN POTABLE WATER

Analysis	Method	Optimum Concentration Range, mg/L	Detection Limit, mg/L	Method Number[1]
Total Fluoride	Colorimetric, SPADNS with Bellack Distillation	0.1-1.4	±0.103	EPA 340.1[2]
Fluoride	Potentiometric, Ion Selective Electrode	0.1-1000	±0.036	EPA 340.2[2]
Fluoride	Electrode Method	0.2-2	---	414-B[3]
Fluoride	SPADNS Method	0-1.4	±0.04	414-C[3]
Standard Test Methods for Fluoride Ion in Water	ASTM Method A (distillation)	0-1.4	±0.089	D1179-A[4]
	ASTM Method B (ion selective probe)	0.1-1000	-3.3<X<0.07	D1179-B[4]
Fluoride	Complexone Method (TENTATIVE)	0.1-2	---	603[3]

REFERENCES TO APPENDIX B

1. Interim Primary Drinking Water Regulations; Amendments. U.S. Environmental Protection Agency. Federal Register 45(168):57332-57, 1980.
2. Methods for Chemical Analysis of Water and Wastes. Revised. U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/4-79-020, 1980.
3. Standard Methods for the Examination of Water and Wastewater, 14th ed. American Public Health Association, American Water Works Association, Water Pollution Control Federation, 1976.
4. Annual of ASTM Standards, Part 31 - Water. American Society for Testing and Materials, 1976.

APPENDIX C
COST CALCULATIONS

CALCULATIONS OF BOTTLED WATER COSTS

1. Determination of Delivery Route Distance: The route distance for each population category considered was based upon an estimate of existing water main distribution length. Since detailed route distance information for various size categories of communities is not available, it seems reasonable to approximate this parameter with water main distribution length since the residents serviced by existing water mains would be the same that require bottled water delivery.

The relationship between distribution main length and population density was developed by Roy F. Weston, Inc.(1) and also incorporated into an EPA Water Reuse Manual.(2)

$$Lm = 125.39\ p_d^{-0.458}$$

where,

Lm = Length of water main/population (miles/1000 people)

P_d = Population density (people/sq. mile)

By assuming a population based on average population for each category, the following list of distribution lengths was developed:

Population*	Distribution Length (Mi.)	Rationale
62	1.0	Minimum value of 1.0 mile chosen
300	1.0	Minimum value of 1.0 mile chosen
750	2.3	Density = 3162 people/sq. mile
1750	5.4	Density = 3162 people/sq. mile
3750	11.6	Density = 3162 people/sq. mile
7500	15.0	Density = 8000 people/sq. mile

*Note: The population selected for each category is an average of the range of population by category assumed in the Water Utility Financing Study.(3)

2. Survey of Bottled Water Distribution: A survey of bottled water bottlers/distributors provided cost information incorporated into a computer model BOTWAT. This model was used with community scenarios representing the different population categories to develop cost estimates of bottled water distribution. The following table lists the various parameters and values used to generate costs.

TABLE C-1-1

INPUT PARAMETERS TO BOTWAT(1)

Annual Interest Rate	12%
Annual Inflation Rate	Not included
Starting Year of Planning Period	1982
Truck Life	9.0 years
Planning Period	20 years
Truck Capacity	1200 gallons in 5 gallon bottles
Frequency of Delivery	2 deliveries/week/residence
Distance to Bottled Water Plant	25 miles round trip
Truck O&M Cost	$0.34/mile
Labor Cost	$9.00/hour
Average Number of Workers/Truck	2.0
Individual Bottled Water Demand	0.5 gallons/capita/day
Capital Cost of Truck	$17,500 minimum, $24,000 average, $29,600 maximum
Container Costs ($/gallon)	0.02 minimum, 0.026 average, 0.048 maximum
Wash, Fill, and Capping Cost ($/gallon)	0.02 minimum, 0.17 average, 0.32 maximum

CALCULATIONS UTILIZED IN DEVELOPING COST ESTIMATES FOR POINT-OF-USE

1. Capital and Operating and Maintenance Costs: Information on point-of-use treatment costs for activated alumina and reverse osmosis devices was obtained through the Water Quality Association[4] from equipment manufacturers of point-of-use devices. Capital costs include the purchase and installation costs of the required number of units for the populations considered. Operating and maintenance costs were developed from a specific replacement criteria based upon manufacturer's information. Supporting information relative to operating and maintenance characteristics was also obtained from a study of defluoridation units in Arizona[5] and the EPA/NSF study on defluoridation.[6]

Capital cost functions are based upon estimate of costs for manufactured equipment plus installation and include 15 percent for engineering and subcontractor fees and 15 percent for miscellaneous contingencies.

Annual operating and maintenance costs were supplied by manufacturers and include replacement of treatment cartridge and once a year servicing schedule, maintenance and labor costs. Costs are based on replacing a regenerated media for activated alumina or membrane element for reverse osmosis.[1]

Cartridge sizes for both activated alumina and reverse osmosis are based upon manufacturers' recommendations for a single household with servicing once a year. For an average household, the estimated water output for drinking and cooking purposes is 2 gpd.[1,7]

The number of household connections (or units) required for the community are based upon the total plant capacity for the entire municipal system divided by an estimated total water use of 300 gpd per household. The following table indicates the number of units corresponding to the production categories:

TABLE C-2-1

POINT-OF-USE UNITS PER PRODUCTION CAPACITY

Plant Capacity MGD	Number of Units
0.01	33
0.03	100
0.08	266
0.22	733
0.53	1766
1.03	3100

2. Equations for Developing Cost Estimates:

Activated Alumina

Capital Costs ($/yr) = $59.11(Q)^{0.905}$

O&M Costs ($/yr) = $310.88(Q)^{0.987}$

where,

Q = Plant Capacity, MGD.

Reverse Osmosis

Capital Costs ($/yr) = $204.87(Q)^{0.905}$

O&M Costs ($/yr) = $488.4(Q)^{0.987}$

where,

Q = Plant Capacity, MGD.

3. Input Parameters for Calculating Capital and O&M Costs:

Purchased equipment including installation

activated alumina	$225/unit
reverse osmosis	$780/unit

Replacement cartridge including labor

activated alumina	$93/year
reverse osmosis	$146/year

4. Filtration: Filtration costs are not included as a pretreatment protection for activated alumina or reverse osmosis. Where filtration is required, additions to the capital and O&M costs can be readily calculated.

For capital costs, the additional cost for installing a filtration unit is $25.00. To calculate the capital cost of point-of-use treatment including filtration, multiply the annual capital cost without filtration by the ratio

$$(U + 25)/U$$

where,

U = initial purchase and installation cost for point-of-use device.

Similarly, multiply the annual O&M cost by the ratio

$$(R + 10)/R$$

to include the cost of replacing the filter cartridge,
where,

R = annual replacement and labor cost per point-of-use device.

Assumptions made regarding filter unit cartridges were:

1. Cost of filter cartridge = $5/cartridge
2. Replacement frequency = 1 time/year
3. Replacement of filter cartridge coincides with point-of-use device cartridge replacement, therefore, no additional labor cost is added for changing the filter cartridge.

C-3

CALCULATIONS UTILIZED IN DEVELOPING COST ESTIMATES FOR REGIONALIZATION

1. Pipeline Size: The size of the pipeline has significant impact on the cost for transmitting water long distances. Smaller diameter pipelines will result in greater friction heads and more energy consumption. With increase in pipe size the energy costs decrease but the cost of the pipe increases. The cost benefits from saving energy will be gradually reduced with the increase in pipe size and will reach an optimum beyond which energy costs are not sensitive to the total costs of the system. Optimum pipeline diameters for the nine size categories were determined incorporating energy-cost considerations applicable to the pumping stations and transmission pipeline.(8) Flow capacities of the pipeline were increased for fire protection and pipe diameters calculated for the different size systems are as follows:

Size System mgd	Pipe Diameter Inches	Percent Added for Fire Protection
0.01	3	100
0.04	3	100
0.14	4	100
0.44	6	100
0.90	10	100
1.55	12	100
8.82	18	50
75.99	54	50
721.98	108	50

2. Capital and Operating and Maintenance Costs: The capital costs for the pipeline include excavation, laying of cast iron pipe, jointing and backfill. The costs do not include costs of a right-of-way and engineering surveys. The capital costs of pumping station include costs of manufactured equipment, housing for the pumping equipment and installation labor. O&M costs are primarily the process energy costs for pumping. Maintenance costs for manufactured material and labor are included.

A survey of 20 water utilities was used as a basis for developing cost estimates for the construction and operation and maintenance of transmission pipelines.

CALCULATIONS FOR DEVELOPING COST ESTIMATES FOR DEVELOPMENT OF AN ALTERNATE SOURCE

1. Capital Costs: The cost estimates for development of alternate source water supplies were determined through application of the WATMAN model.[1] Supporting information, such as costs for treatment,[9] pipeline,[8] well drilling and pumping equipment[10] obtained through communications with various manufacturers and manufacturers' associations,[11] have been used wherever applicable.

The construction costs include the following:

1. site work (excavation and/or preparation)
2. purchased manufactured equipment
3. concrete
4. labor
5. support plumbing and instrumentation
6. housing
7. 15 percent fee for miscellaneous and contingency
8. 15 percent fee for engineering and subcontracts.

Other factors are:

1. cost of land for impounded resevoirs, $1000/acre
2. wells, drilled 100 feet deep, 12 inch diameter
3. total dynamic head for pumping from well to ground storage, 150 feet
4. raw water intake pumping for surface water sources, total dynamic head 50 feet
5. detention time in flocculator, 30 minutes
6. detention time in clarifier, 4 hours
7. filtration rate, 2 gpm/sqft.

2. Operation and Maintenance Costs: All operation and maintenance costs functions include:

1. maintenance material
2. labor
3. energy
4. cost of chemicals for operating.

REFERENCES TO APPENDIX C

1. Deb, A.K., et al., Alternative Technologies for Small Water System Management. Supported by National Science Foundation, Grant No.: 1 SP 80-15075. R.F. Weston, Inc., 1982.
2. Donovan, J.F. and Bates, J.E., Guidelines for Water Reuse. U.S. Environmental Protection Agency, EPA-600/8-80-036, 1980.
3. Water Utility Financing Study. U.S. Environmental Protection Agency, Office of Drinking Water, 1980.
4. Water Quality Association, Douglas R. Oberhamer, Executive Director, 477 E. Butterfield Road, Lombard, Illinois, 60145.
5. Defluoridation Study for the Arizona Department of Health Services. PRC (Planning Research Company) Toups Corp., 1979.
6. EPA/NSF Study of Defluoridation of Drinking Water in Small Communities and Point-of-Use Reduction of Volatile Halogenated Organic Contaminants from Drinking Water. U.S. Environmental Protection Agency, Ninth Quarterly Report, 1983.
7. Perry, D., et al., Development of Basic Data and Knowledge Regarding Organic Removal Capabilities of Commercially Available Home Water Treatment Units Utilizing Activated Carbon. Phase 3/Final Report-Supplemental Data. Gulf South Research Institute, 1981.
8. Deb, A.K., Optimum energy cost design of a pipeline. Journal of Pipelines 1:191-196, 1981.
9. Estimating Water Treatment Costs: Volumes 2 and 3. U.S. Environmental Protection Agency, EPA-600/2-79-162b, EPA-600/2-79-162C, 1979.
10. Cost of Wells and Pumps. Technical Letter 10. Illinois State Water Survey, 1968.
11. Personal communication with various manufacturers and manufacturers' associations. R. F. Weston, Inc., 1982.

APPENDIX D

ENGLISH/METRIC CONVERSIONS

English Unit	Multiply By	Metric (International System) Units
LENGTH		
inch (in)	2.54	centimeters (cm)
feet (ft)	30.48 0.3048	centimeters (cm) meters (m)
mile (mi)	1.61	kilometers (km)
MASS		
pound (lb)	0.454 453.6	kilograms (kg) grams (g)
ton (t - long)	1016.0	kilograms (kg)
ton (t - short)	907.185	kilograms (kg)
VOLUME		
cubic feet (cuft; cuft	28.32	liters (L)
1 cubic foot = 7.48 gallons	0.028	cubic meters (m^3)
gallon (gal)	3.785	liter (L)

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FLOW RATES

feet per second (ft/sec)	0.305	meter per second (m/sec)
gallons per minute (gpm)	5.45	cubic meters per day (m^3/day)
694.4 gpm = 1 million gallons per day (mgd)		
million gallons per day (mgd)	3785.00	cubic meters per day (m^3/day)
gallons per minute per square foot (gpm/sqft)	40.7	liters per minute per square meter (L/min/m^2)

POWER

horsepower (hp)	0.746	kilowatts (kw)

PRESSURE

pounds per square inch (psi)	0.068 0.070	atmospheres (atm) kilograms per square centimeter (kg/cm^2)
atmosphere	101.64	kilo Pascals (kPa)
pounds per cubic foot (lb/cuft; lb/cuft)	16.02	kilograms per cubic meter (kg/m^3)

AREA

square feet (sqft)	0.093	square meters (m^2)
square miles (sq mi)	260	hectares (ha)